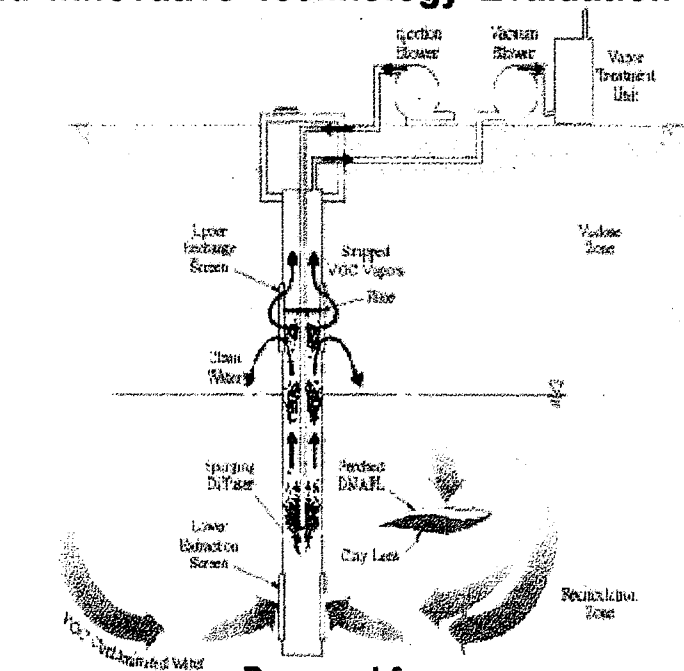
Technology Evalutation Report

for the

NoVOCs™ Technology Evaluation

Superfund Innovative Technology Evaluation Program



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National Risk Management Research Laboratory
Cincinnati, Ohio

Prepared by:

Tetra Tech EM Inc.
San Diego, California

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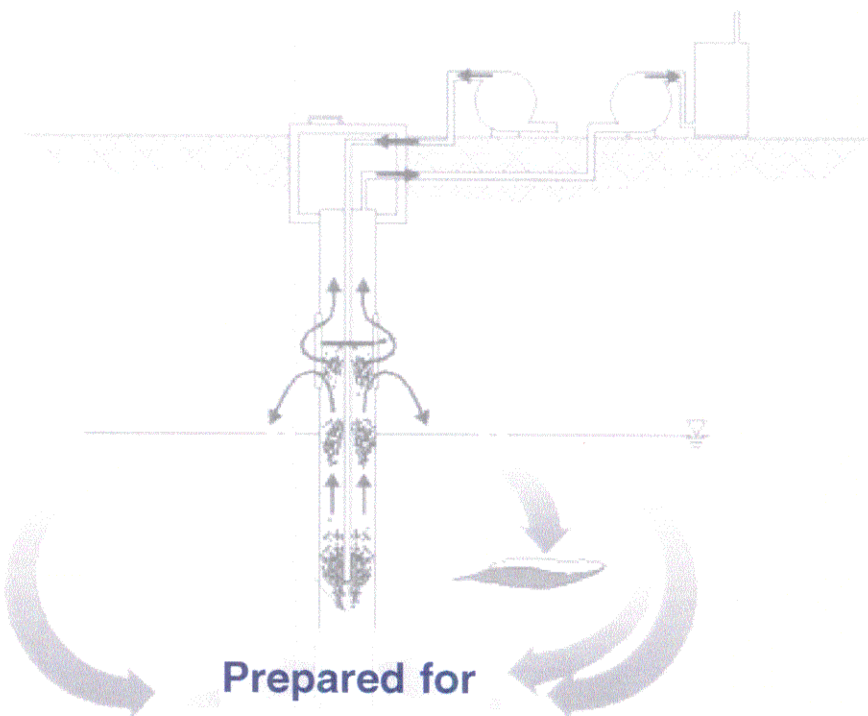
Hydrogeological Investigation of the Aquifer Treated by the NoVOCs™ System

Naval Air Station North Island
San Diego, California



Prepared for

U.S. Environmental Protection Agency
National Risk Management Laboratory
Superfund Innovative Technology Evaluation Program
Cincinnati, Ohio

Prepared by

Tetra Tech EM Inc.
San Diego, California

August 30, 1999

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ACRONYMS AND ABBREVIATIONS

bgs	Below ground surface
cm/sec	Centimeters per second
CPT	Cone penetrometer test
DCA	Dichloroethane
DCE	Dichloroethene
DFT	Dipole flow test
DNAPL	Dense nonaqueous phase liquid
Eh	Reduction/oxidation potential
EPA	U. S. Environmental Protection Agency
ft/day	Feet per day
ft/ft	Feet per foot
ft^2/day	Square feet per day
gpm	Gallons per minute
gpm/ft	Gallons per minute per foot
g/cm^3	Grams per cubic centimeter
IR	Installation Restoration
MACTEC	MACTEC Inc.
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
MLLW	Mean lower low water
mv	Millivolts
NAS	Naval Air Station
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric turbidity units
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear aromatic hydrocarbon
PCE	Tetrachloroethene
psi	Pounds per square inch
PVC	Polyvinyl chloride
scfm	Standard cubic feet per minute
SITE	Superfund Innovative Technology Evaluation
SVOC	Semivolatile organic compound
1,1-TCA	1,1-Trichloroethane
TDS	Total Dissolved Solids
TCE	Trichloroethene

ACRONYMS AND ABBREVIATIONS (continued)

Tetra Tech	Tetra Tech EM Inc.
VOC	Volatile organic compound
μmhos/cm	Micromhos per centimeter

EXECUTIVE SUMMARY

In support of the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program, Tetra Tech EM Inc. (Tetra Tech) is evaluating the MACTEC Inc. (MACTEC) NoVOCs™ in-well volatile organic compound (VOC) stripping system at Installation Restoration (IR) Site 9 at Naval Air Station (NAS) North Island in San Diego, California. The NoVOCs™ system is a patented recirculating well that is designed for the in situ remediation of groundwater contaminated by VOCs.

In April 1998, the Navy initiated operation of the NoVOCs™ system. By June 1998, the pumping rate had been reduced from the design rate of 25 gallons per minute (gpm) to approximately 5 gpm because not all water pumped at higher rates could be injected into the aquifer. The NoVOCs™ system was shut down on June 19, 1998, to evaluate the cause of the problem. Suspected causes for the poor injection performance included (1) biofouling or scaling of the screen intervals and formation near the NoVOCs™ system, (2) design problems with the NoVOCs™ well, in particular the sizing of the recharge screen, and (3) possible differences in hydraulic characteristics between the upper and lower portions of the aquifer.

EPA directed Tetra Tech to conduct the hydrogeological study at the demonstration site to provide information on the recharge capacity of the NoVOCs™ system and the hydraulic characteristics of the aquifer in the vicinity of the NoVOCs™ system. The groundwater study included: (1) a tidal influence study to evaluate natural variations in water level at the site due to tides in San Diego Bay, and (2) a series of groundwater pumping tests in the shallow and deep portions of the aquifer, including step drawdown tests, a 32-hour constant pumping rate test, an injection test, and a dipole flow test to evaluate the aquifer characteristics in the vicinity of the NoVOCs™ system.

The hydrogeological investigation of the aquifer treated by the NoVOCs™ system has yielded valuable information regarding the hydraulic characteristics of the aquifer, pumping and injection capacities of the NoVOCs™ well, and defects in the NoVOCs™ well. The conclusions of the investigation are as follows:

1) The tested aquifer is in good hydraulic communication with San Diego Bay. Groundwater levels at different depths within the aquifer are all influenced by tidal fluctuations in San Diego Bay. The tidal influence of the aquifer is demonstrated by the drawdown data collected from the observation wells during the constant discharge pumping test of the NoVOCs™ well.

2) The groundwater levels must be corrected for tidal effects to allow the calculation of aquifer parameters and mean groundwater elevations. In addition, the mean groundwater elevations must be corrected for density effects to allow determination of groundwater flow patterns.

After tidal and density corrections, the mean equivalent fresh water head contour maps were generated.

3) The aquifer hydraulic tests show that the upper and lower aquifer zones are in good hydraulic communication. Drawdown responses were observed in both aquifer zones during the constant discharge pumping test in the upper aquifer zone and the step-drawdown tests in the upper and lower aquifer zones.

4) Groundwater generally flows to the west or northwest in both of the upper and lower aquifer zones. The horizontal hydraulic gradient in both aquifer zones is relatively flat, ranging from 0.005 to 0.01.

5) Two methods were developed for tidal correction of groundwater drawdown data obtained during the constant discharge pumping test. The methods involve using the tidal influence study data collected in April 1998 to calculate the tidal efficiency and time lag for each of the observation wells. The estimated tidal efficiency ranges from 0.05 to 0.1 in different tidal cycles at different wells; and time lags range from 46 to 96 minutes.

6) Observed drawdown data collected during the constant discharge pumping test were corrected using the two new tidal correction methods. The corrected drawdown (that is, drawdown data with the tidal effects removed) using both methods correlates well with each other and reflects typical pumping test responses. The corrected drawdown matches reasonably well with Neuman type curves for the aquifer parameter estimation.

7) The aquifer hydraulic parameters were estimated based on the tidally corrected groundwater drawdown data for the constant discharge pumping test. The average hydraulic conductivity was estimated as 29 feet per day (ft/day) or 0.01 centimeters per second (cm/sec). The average aquifer storativity and specific yield are 0.004 and 0.07, respectively. The average ratio of horizontal to vertical hydraulic conductivity is estimated at 5.7.

8) Specific capacity and efficiency of the NoVOCs™ well were estimated based on the step-drawdown tests and water injection test conducted at the NoVOCs™ well. The calculated average specific capacities are 1.48 gallons per minute per foot (gpm/ft) for the upper screened interval during pumping, 1.50 gpm/ft during injection, and 3.22 gpm/ft for the lower screened interval during pumping. The calculated average well efficiencies are 82 percent for the upper screened interval during pumping, 97 percent during injection, and 91 percent for the lower screened interval during pumping. The 97-percent well efficiency for the upper screened injection is for injection of clean tap water.

9) The radius of influence, as defined as the distance from the pumping well to an observation well at which drawdown can be positively identified (0.01 feet), was at least 100 feet during the constant discharge pumping test with a pumping rate of 20 gallons per minute (gpm).

10) No positive (recharge) or negative (flow barrier) boundaries are evident from the constant discharge pumping test data.

11) The injection test results show that the maximum flow of clean tap water that can be injected through the upper screen of the NoVOCs™ well is 25 gpm. At that injection rate, the water level will rise 17 feet and reach the ground surface.

12) The video survey of the NoVOCs™ well revealed a manufacturing defect in the upper well screen. The screen slots are unevenly cut, and about 30 percent of the slots do not completely penetrate the PVC casing. This defect affects the well efficiency of the upper screened interval and may reduce the available water level rise in the NoVOCs™ well during recharge to the aquifer through the upper screen.

13) The video survey also revealed significant fouling of the NoVOCs™ well screens by iron precipitation and microbiological growth. Such fouling may impair the performance of the NoVOCs™ system by obstructing the well screen and filter pack.

14) The findings of the aquifer tests and tidal study of the aquifer treated by the NoVOCs™ system indicate that the aquifer hydraulic conditions are suitable for application of the NoVOCs™ technology. The NoVOCs™ well as designed should be able to extract and inject a flow rate of 20 gpm based on the aquifer hydraulic characteristics.

1.0 INTRODUCTION

In support of the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program, Tetra Tech EM Inc. (Tetra Tech) is evaluating the MACTEC Inc. (MACTEC) NoVOCs™ in-well volatile organic compound (VOC) stripping system at Installation Restoration (IR) Site 9 at Naval Air Station (NAS) North Island in San Diego, California. The NoVOCs™ system is a patented recirculating well that is designed for the in situ remediation of groundwater contaminated by VOCs. A vicinity map, site location map, and site plan are presented as Figures 1-1, 1-2, and 1-3.

In April 1998, the Navy initiated operation of the NoVOCs™ system. The EPA SITE Program evaluation of the NoVOCs™ system also began in April 1998, and included collection of air and groundwater samples from the NoVOCs™ system and surrounding monitoring points. The evaluation was conducted in accordance with the draft final "Technology Evaluation Plan/Quality Assurance Project Plan for the MACTEC NoVOCs™ Technology Evaluation at NAS North Island" (Tetra Tech 1998). By June 1998, the pumping rate had been reduced from the design rate of 25 gallons per minute (gpm) to approximately 5 gpm because not all water pumped at higher rates could be injected into the aquifer. Based on discussions between the Navy and the technology developer, the system was shut down on June 19, 1998, to evaluate the cause of the poor injection performance. Suspected causes for the poor injection performance included (1) biofouling or scaling of the screen intervals and formation near the NoVOCs™ system, (2) design problems with the NoVOCs™ well, in particular the sizing of the recharge screen, and (3) possible differences in hydraulic characteristic between the upper and lower portions of the aquifer. This report presents the results of a hydrogeological investigation to assess the hydraulic characteristics of the aquifer that may affect the NoVOCs™ system performance.

EPA directed Tetra Tech to conduct the hydrogeological study at the demonstration site to obtain information on the recharge capacity of the NoVOCs™ system and the aquifer hydraulic characteristics in the vicinity of the NoVOCs™ system. The hydrogeological study included: (1) a tidal influence study to evaluate natural variations in water level at the site due to tides in San Diego Bay, and (2) a series of aquifer hydraulic tests in the shallow and deep portions of the aquifer, including step drawdown tests, a 32-hour constant discharge pumping test, an injection test, and a dipole flow test to evaluate the aquifer characteristics in the vicinity of the NoVOCs™ system.

This report presents background information on the NoVOCs™ system and IR Site 9, documents the field methods and procedures implemented during the groundwater study, presents the study results, discusses the data analysis and interpretation, and presents conclusions based on the information obtained. The remainder of this section presents information on the EPA SITE program and the hydrogeological study objectives.

1.1 SITE PROGRAM

SITE was established by EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986. The SITE program was established to accelerate the development, evaluation, and use of innovative technologies to remediate hazardous waste sites. The evaluation portion of the SITE program focuses on technologies in the pilot- or full-scale development stage. The evaluations are intended to collect performance data of known quality. In support of this portion of the program, a series of aquifer tests were conducted to assist in evaluating the NoVOCs™ system by providing a greater understanding of the site hydrogeology.

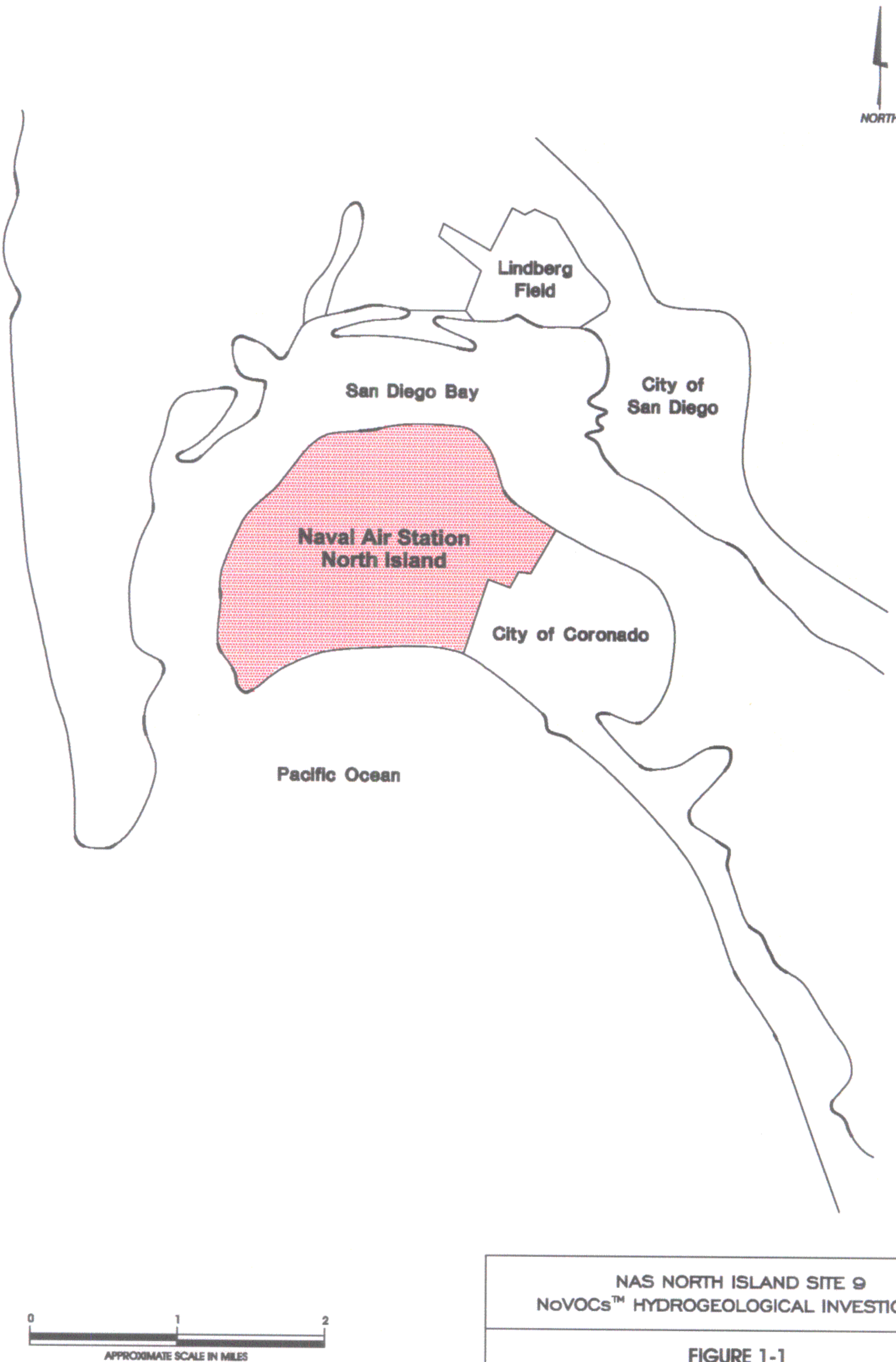
1.2 PROJECT OBJECTIVES

The overall objective of the groundwater study was to assess hydraulic characteristics of the aquifer in the vicinity of the NoVOCs™ system at the demonstration site. In support of this objective, the specific objectives of the groundwater study were to: (1) document groundwater elevation change (water level) in selected wells due to tidal influence, and (2) conduct a series of aquifer hydraulic tests to assess hydrogeologic conditions in the vicinity of the NoVOCs™ system.

Aquifer hydraulic tests of the NoVOCs™ well (IW-01) were conducted to estimate or assess the following:

- Well efficiencies of the two screened intervals of the NoVOCs™ well: the outer casing is screened at 43 to 47 feet below ground surface (bgs)(-21.3 to -25.3 feet relative to mean lower low water[MLLW]) and 72 to 78 feet bgs (-50.3 to –56.3 feet MLLW).
- Hydraulic parameters of the upper and lower portions of the aquifer, including estimation of hydraulic conductivity, transmissivity, storativity, and aquifer anisotropy.
- The radius of influence established during pumping.

- The presence of hydraulic barriers that may affect hydraulic communication between the upper and lower zones of the aquifer.

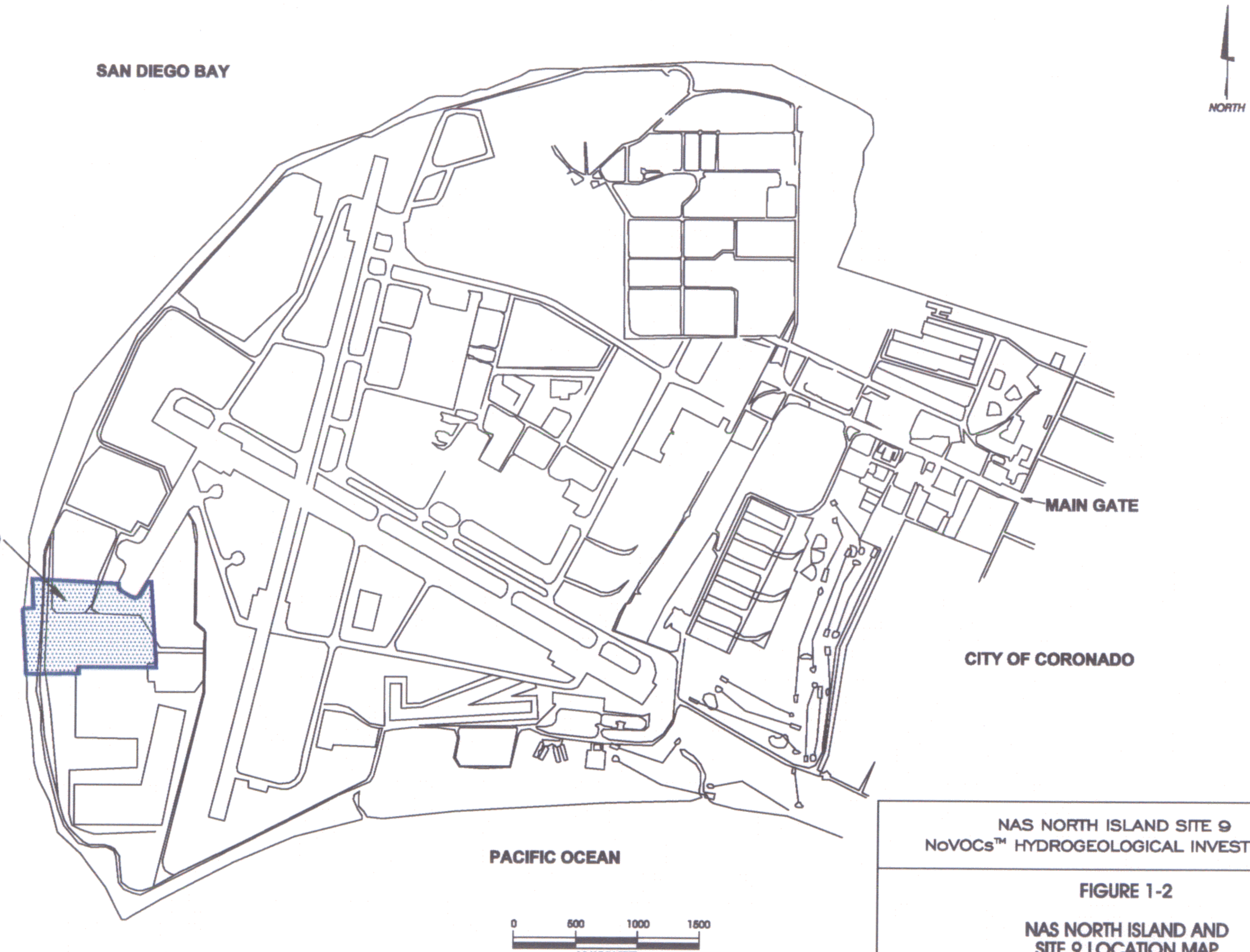


NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 1-1

VICINITY MAP

Tetra Tech EM Inc.



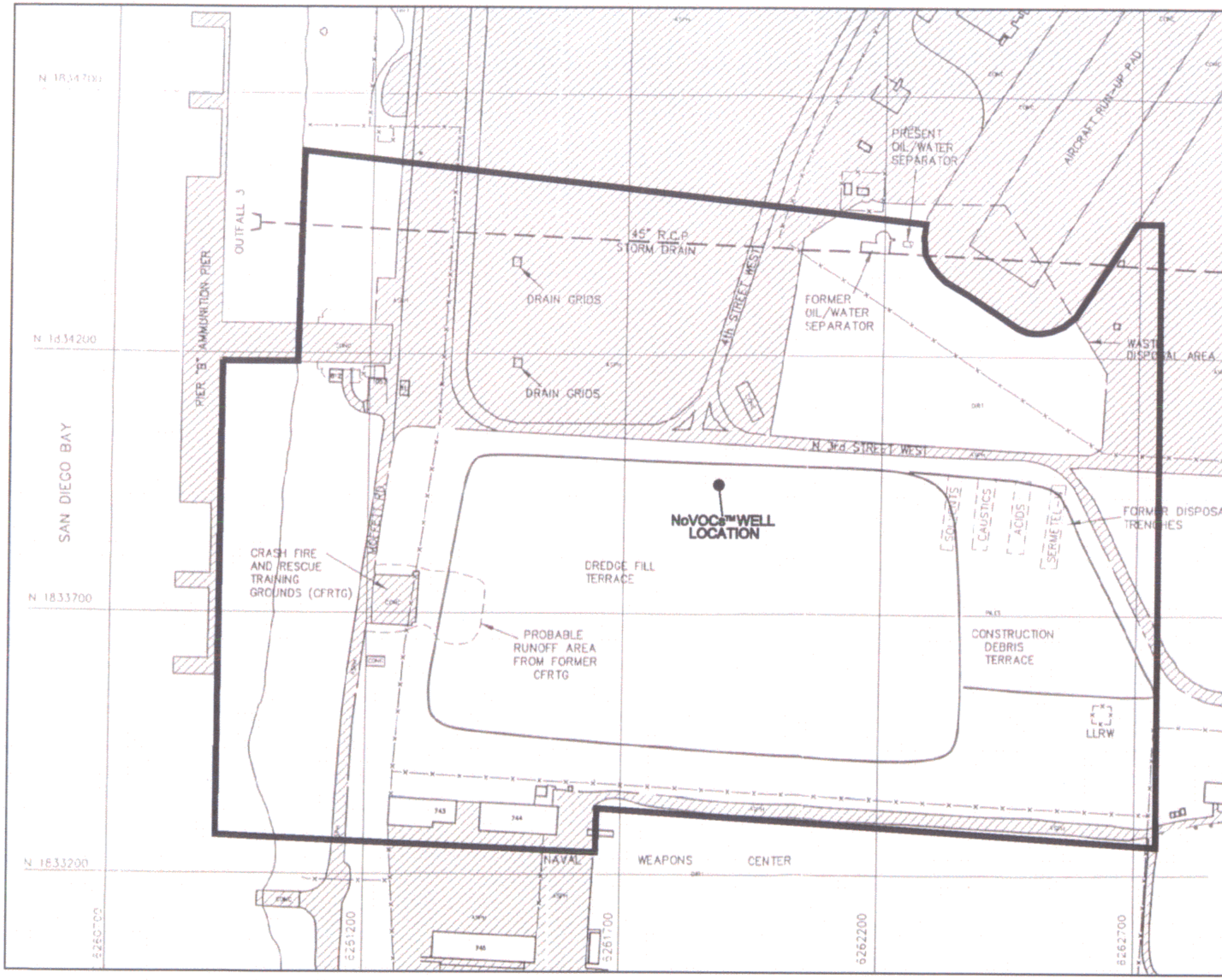
SOURCE: MODIFIED FROM BROWN AND CALDWELL 1983.

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 1-2

NAS NORTH ISLAND AND
SITE 9 LOCATION MAP

Tetra Tech EM Inc.



NORTH

LEGEND

	FENCE
	ROAD AND STREET
	BUILDING
	PAVEMENT (CONCRETE OR ASPHALT)
	TERRACE BORDERS
LLRW	LOW-LEVEL RADIOACTIVE WASTE STORAGE AREA
	STORM DRIAN
	SITE 9 BOUNDARY

NOTES:

1. BASE MAP ADAPTED FROM PHOTOGRAMMETRY BY BECHTEL NATIONAL, INC., 1994.
2. ELEVATION DATUM IS MEAN LOWER LOW WATER.
3. COORIDINATES ARE IN THE CALIFORNIA COORDINATE SYSTEM (1983) ZONE 6 BASED ON THE NORTH AMERICAN DATUM (1983).

0 250 500

SCALE IN FEET

SOURCE: MODIFIED FROM JACOBS 1994

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 1-3

SITE 9 CHEMICAL WASTE DISPOSAL AREAS

Tetra Tech EM Inc.

2.0 BACKGROUND

This section describes the NoVOCs™ system and the associated groundwater monitoring system at NAS North Island. This section also provides information on site conditions, including site history, topography, geology, hydrogeology, and soil and groundwater contamination. In addition, this section identifies the locations and describes the construction of wells installed to investigate the hydrogeology of the site.

2.1 THE NoVOCs™ SYSTEM

This section provides a general description of the NoVOCs™ system at NAS North Island and describes the groundwater monitoring system for evaluating the NoVOCs™ system performance.

2.1.1 General Description

The NoVOCs™ system is a patented in-well stripping process (U.S. Patent No. 5,180,503) for in situ removal of VOCs from groundwater. A diagram of the treatment process is shown in Figure 2-1. In this process, air injected into a specially designed well simultaneously creates an air-lift pump and an in situ stripping reactor to circulate and remediate groundwater (EG&GE 1996).

The NoVOCs™ system consists of a well casing installed in the contaminated saturated zone, with two screened intervals below the water table and an air injection line extending into the groundwater within the well. Contaminated groundwater enters the well through the lower screen and is pumped upward within the well by pressurized air supplied through the air injection line, creating an air-lift pump effect. As the water is air-lifted within the well, dissolved VOCs in the water volatilize into the rising air bubbles and are transported to the upper portion of the well. The treated water rises to a deflector plate and is forced out the upper screen. The treated water is recharged to the aquifer, and the stripped VOC vapors are removed from the subsurface by a vacuum applied to the upper well casing (EG&GE 1996). The stripped vapors then are treated by the Thermatrix flameless oxidation process. The equipment used to operate the NoVOCs™system, including blowers, control panel, and air temperature, pressure, and flow rate gauges is housed in an on-site control trailer.

2.1.2 NoVOCs™ Monitoring System at NAS North Island

At NAS North Island, one NoVOCs™ well has been installed to remediate a portion of the aquifer downgradient of a contaminant source area. Assuming the designed pumping rate of 25 to 30 gpm and a total air flow rate of 120 standard cubic feet per minute (scfm), the radius of influence of the NoVOCs™ well for this site is predicted to be at least 90 feet (EG&GE 1997). To evaluate the accuracy of this prediction and to obtain information on the horizontal and vertical extent of the NoVOCs™ treatment cell and assess changes in contaminant concentrations within the treatment cell, two ½-inch outer diameter piezometers (PZ-01 and PZ-02) and 10 2-inch outer diameter groundwater observation wells (MW-45 through MW-54) were installed.

Figure 2-2 shows a plan view of the location of the NoVOCs™ well and observation wells. Figure 2-3 shows a generalized cross-section of the NoVOCs™ well, piezometers, and observation wells. The two piezometers were installed within the sand pack of the NoVOCs™ well: one adjacent to the NoVOCs™ recharge screen (PZ-01), and one adjacent to the NoVOCs™ intake screen (PZ-02). The natural groundwater flow direction across the site is generally to the west. Seven cross-gradient observation wells were installed at four distances from the NoVOCs™ well, as follows: a cluster of three wells 30 feet from the NoVOCs™ well (observation wells MW-45, MW-46, and MW-47), a well pair 60 feet from the NoVOCs™ well (observation wells MW-48 and MW-49), and single observation wells 90 and 105 feet from the NoVOCs™ well (observation wells MW-50 and MW-51). Two downgradient observation wells (MW-52 and MW-53) were installed as a pair approximately 100 feet from the NoVOCs™ well, and a single observation well (MW-54) was also installed 100 feet upgradient of the NoVOCs™ well. Each observation well was screened at one of the following three intervals: at the top of the treatment zone (between approximately 41 and 47 feet bgs [-19.1to -25.0 feet MLLW]), in the middle of the treatment zone (between approximately 49 and 62 feet bgs [-35.1 to -40.4 feet MLLW]), and at the bottom of the treatment zone (between approximately 67 and 78 feet bgs [-43.6 to -58.0 feet MLLW]). A summary of well screen intervals for the individual wells is presented in Table 2-1.

2.2 SITE HISTORY

NAS North Island is the largest naval aviation complex on the West Coast and is home to two aircraft carriers and the Third Fleet flagship, USS Coronado. NAS North Island is located at the northern end of the peninsula that forms San Diego Bay and is bordered by the City of Coronado to the east, the Pacific Ocean to the south, and San Diego Bay to the north and west (Figure 1-1). The 2,806-acre complex,

officially commissioned in 1917, provides aviation support services to the fleet, aircraft maintenance, airfield operations, pierside services, and logistics. The mission of NAS North Island is to maintain and operate facilities and to provide services and materiel that support operation of aviation activities and units of the Operating Forces of the Navy, as well as other units as designated by the Chief of Naval Operations.

Past hazardous waste disposal practices at NAS North Island have resulted in soil and groundwater contamination. The Navy has undertaken investigations to determine the extent of contamination and possible cleanup methods as part of the IR Program. Under the IR Program, 14 contaminated areas have been designated IR sites, one of which is Site 9 (Figure 1-2).

Site 9, the 40-acre former chemical waste disposal area, is located on the western end of NAS North Island. Site 9 operated from the 1940s to the mid-1970s and consisted of three major waste disposal areas: a shallow pit used for disposal of liquid wastes (located within the waste disposal area shown in Figure 1-3); four parallel trenches each containing different types of wastes (solvents, caustics, acids, and semisynthetics consisting of ceramic and metallic compounds); and a large unimproved area used for burying drums containing unidentified chemical wastes located south of the NoVOCs™ well. An estimated 32 million gallons of waste were disposed of at Site 9 over its 30 years of operation (Jacobs 1995a).

Contamination from these disposal areas has migrated to the underlying groundwater. Although there is no official history of chemical disposal for most of Site 9 outside of the three disposal areas, groundwater contamination is widespread throughout the site. Elevated levels of chlorinated solvents and their breakdown products, as well as petroleum hydrocarbons and metals, are present in groundwater at Site 9. Based on the high dissolved concentrations of chlorinated solvent compounds, the presence of dense nonaqueous phase liquids (DNAPL) in the subsurface is suspected.

The Navy selected a location immediately south of the intersection of 4th Street West and North 3rd Street West to install the NoVOCs™ system (Figure 1-3). Cone penetrometer test (CPT) boreholes advanced at the proposed NoVOCs™ location provided additional characterization of subsurface lithology and confirmed that significant groundwater contamination was present (Bechtel 1998).

2.3 SITE TOPOGRAPHY

The topography of the northern half of Site 9 is relatively flat with an elevation of approximately 13 feet above MLLW. It has virtually no relief and is covered by asphalt paving. The southern half of the site is unpaved, and is almost entirely covered by a terrace composed of hydraulic dredge spoils. The terrace has an elevation of approximately 23 feet above MLLW along its north face and slopes gently southward to approximately 18 feet above MLLW (Jacobs 1994). Topographic elevations and surface features are shown in Figure 2-4. The NoVOCs™ well is located on the terrace at a surface elevation of approximately 22 to 23 feet above MLLW.

2.4 REGIONAL AND SITE GEOLOGY

This section discusses the regional and site geology for Site 9.

2.4.1 Regional Geology

NAS North Island is situated in the coastal portion of the Peninsular Range Geologic Province. This region is underlain by a basement complex of late Cretaceous undifferentiated igneous rocks of the Southern California Batholith and Jurassic prebatholithic metavolcanic rocks. The basement complex is nonconformably overlain by a sedimentary succession of marine and nonmarine rocks that were deposited within the San Diego embayment. These rocks range in age from Late Cretaceous to Recent. The most abundant deposits of the embayment are gently folded and faulted Eocene marine, lagoonal, and nonmarine rocks that thin eastward and trend northwest.

2.4.2 Site Geology

Site 9 is underlain by artificial fill to a depth of approximately 15 feet bgs in the vicinity of the NoVOCs™ well. The artificial fill in this area varies in thickness. The terrace is composed of hydraulic fill derived from dredging the San Diego Bay and consists of fine-grained, loose sand. In addition, in the immediate vicinity of the site, the former Whaler's Bight, a shallow lagoon formerly present at the western edge of North Island, was filled with sediments during the early part of the twentieth century. Below the fill material is the Bay Point Formation, a poorly consolidated, fine- and medium-grained fossiliferous sandstone (Kennedy 1975).

The depositional environment of the site was lagoonal and shallow marine. Sediment accumulated on the southern portion of North Island generally from northward transport of sediment along the shore. As described below, most of the uppermost sediments at the site are composed of fine-grained sand, with varying amounts of silt and medium-grained sand. Two thin silt and clay layers are present in the subsurface at the site and are likely to be continuous in the vicinity of the site, based on observations in the numerous borings and wells installed at the site (Bechtel 1998).

The first fine-grained layer is a thin (2 to 5 feet thick) clay, silt, and clayey sand layer designated as "A clay/silt" (Jacobs 1994). A clay/silt occurs at approximately 35 to 40 feet bgs and is present beneath Site 9 (Jacobs 1994). Recent investigations by Bechtel have indicated that the A clay/silt is continuous from the proposed NoVOCs™ well locations west to the shoreline wells. Beneath the unconsolidated sediments is a sandstone layer at approximately 90 feet bgs. The second layer is the B clay, located approximately 105 feet bgs that also appears to be continuous in the vicinity of the site. The location of a geologic cross-section is shown in Figure 2-5, and the cross-section depicting the subsurface geology of the site is shown in Figure 2-6.

Boring S9-SB-34 located near the NoVOCs™ well encountered mostly sand and silty sand. The A clay/silt was encountered at 35.5 feet bgs, dense sands were encountered between 60 and 61 feet bgs and 65 to 67.5 feet bgs, and a thin cemented sandstone layer was encountered at 79 feet bgs. In addition, the sand fractions of the sands and silty sands ranged from very fine- to coarse-grained and contained various quantities of shell fragments. The log for boring S9-SB-34 is provided in Appendix A.

2.5 SITE HYDROGEOLOGY

The generally accepted hydrogeologic model for islands and peninsulas surrounded by salt water is a lens-shaped body of fresh water resting isostatically atop salt water because of density differences. At Site 9, groundwater occurs at approximately 8 feet bgs (5 feet above MLLW). The upper 110 feet of the saturated zone contains an unconfined aquifer with a thin (5 to 20 feet), discontinuous fresh water lens, a brackish mixing zone (30 to 100 feet), and a seawater wedge intruding inland. Values for some of the hydrogeological parameters of the site are as follows (Jacobs 1995b):

- Hydraulic Gradient: 0.0008 foot per foot (ft/ft) over most of the site, but steepens near the shoreline to 0.006 ft/ft
- Transmissivity: 1,195 square feet per day (ft^2/day)

- Specific yield: 3.2×10^{-1} (dimensionless)
- Hydraulic Conductivity: 12 feet per day (ft/day) or 4.2×10^{-3} centimeters per second (cm/sec)
- Effective Porosity: 0.25 (dimensionless)

In general, the hydraulic gradient is toward the west, varying between southwest and northwest. The groundwater is tidally influenced.

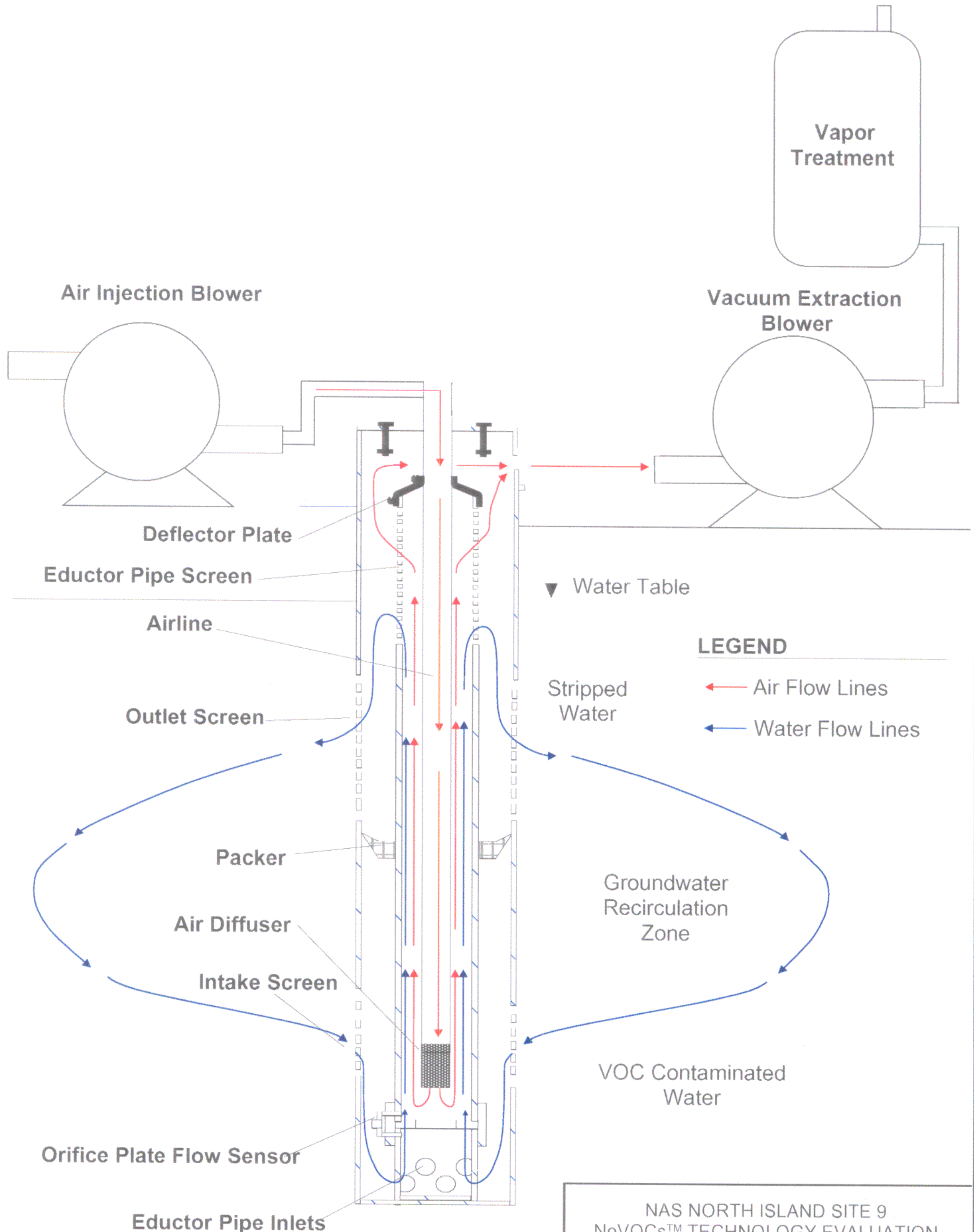
The distribution of groundwater contamination suggests that the general flow of groundwater is toward the west. Contaminants associated with the site have been detected in pore water of San Diego Bay, west of Site 9 (SPARWAR Systems Center 1998). A survey of pore water concentrations of VOCs was conducted in the spring of 1998 in the upper 5 feet of sediment adjacent to and west of Site 9. The results of the survey documented that VOCs were present in the pore water at depths of approximately 20 to 30 feet below MLLW. The data suggest that contaminants are migrating west from Site 9, at a depth consistent with the A clay/silt layer, and discharging to the bay through pore water interchange with the bay water (Bechtel 1998).

2.6 SOIL AND GROUNDWATER CONTAMINATION

Based on findings from previous investigations at the site (Jacobs 1995a,b), high concentrations of chlorinated solvents, chlorinated solvent breakdown products, petroleum hydrocarbons, and metals are present in the saturated and unsaturated zones. The major contaminants detected in groundwater are chlorinated aliphatic hydrocarbon solvents (tetrachloroethene [PCE], trichloroethene [TCE], and 1,1,1-trichloroethane [1,1,1-TCA]) and their breakdown products (dichloroethane [DCA], dichloroethene [DCE], and vinyl chloride); lower concentrations of aromatic hydrocarbons (benzene, toluene, ethylbenzene, and xylene); and heavy metals. Because of the high concentrations of chlorinated solvent compounds in groundwater above the B clay, DNAPL occurrences are suspected at several locations beneath Site 9. If present, DNAPL may act as a long-term source of dissolved-phase contamination in the unconfined aquifer.

Contaminants in soils consist of heavy metals, VOCs, and semivolatile organic compounds (SVOC). Eighteen priority pollutant VOCs were detected in soil samples with individual compound concentrations of up to 3,600 milligrams per kilogram (mg/kg). Fourteen priority pollutant SVOCs, including

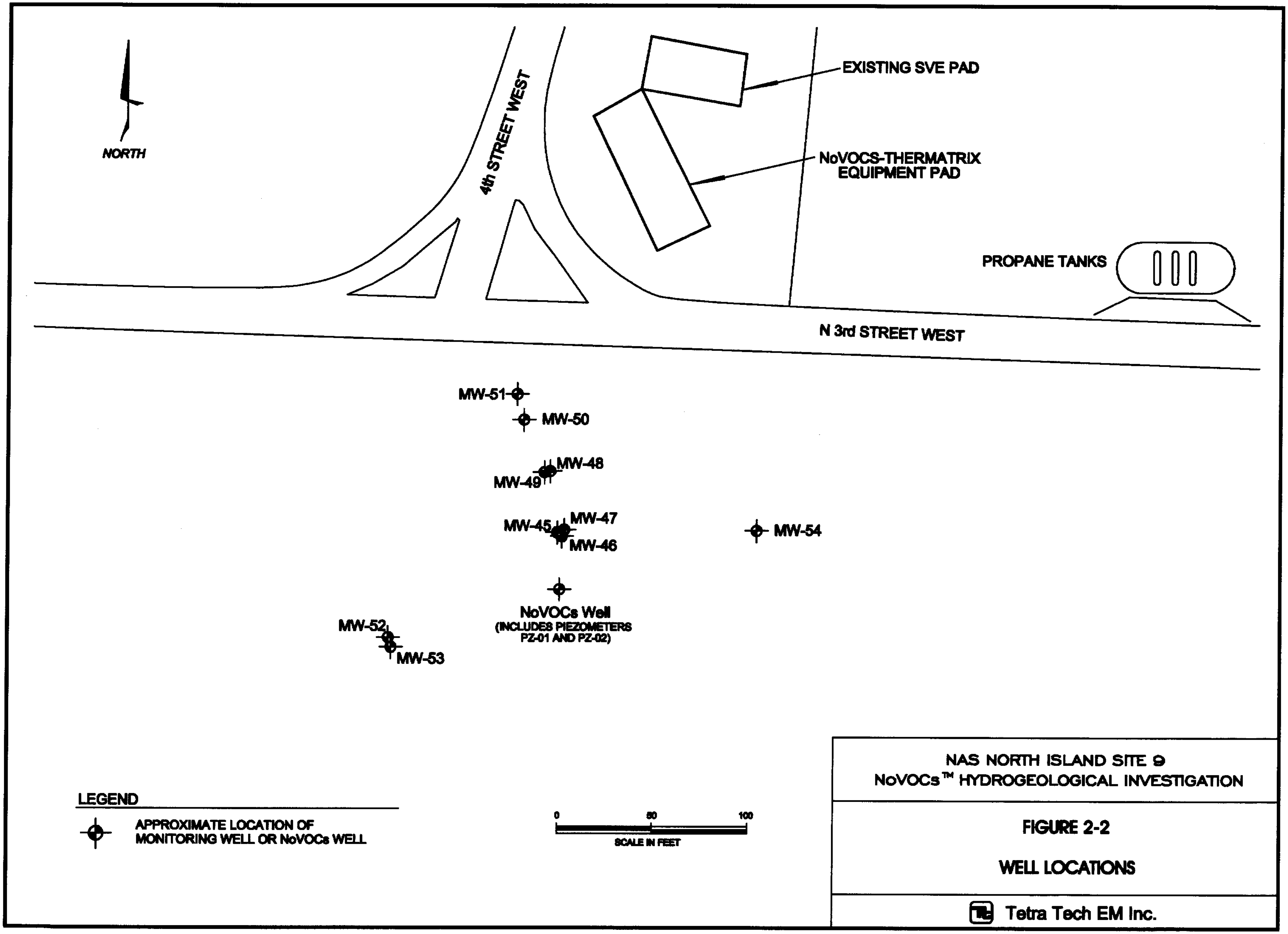
polynuclear aromatic hydrocarbons (PAH), were detected in soil samples with individual compound concentrations up to 1,668 mg/kg. In the former release areas, soils reportedly are virtually saturated with VOCs (Jacobs 1995a). In addition, large quantities of VOCs are believed to have evaporated from saturated soils and groundwater into the vadose zone. Elevated levels of TCE, PCE, and toluene have been detected in soil gas within the vadose zone.



NAS NORTH ISLAND SITE 9
NoVOCs™ TECHNOLOGY EVALUATION

FIGURE 2-1
NoVOCs™ SYSTEM

Tetra Tech EM Inc.

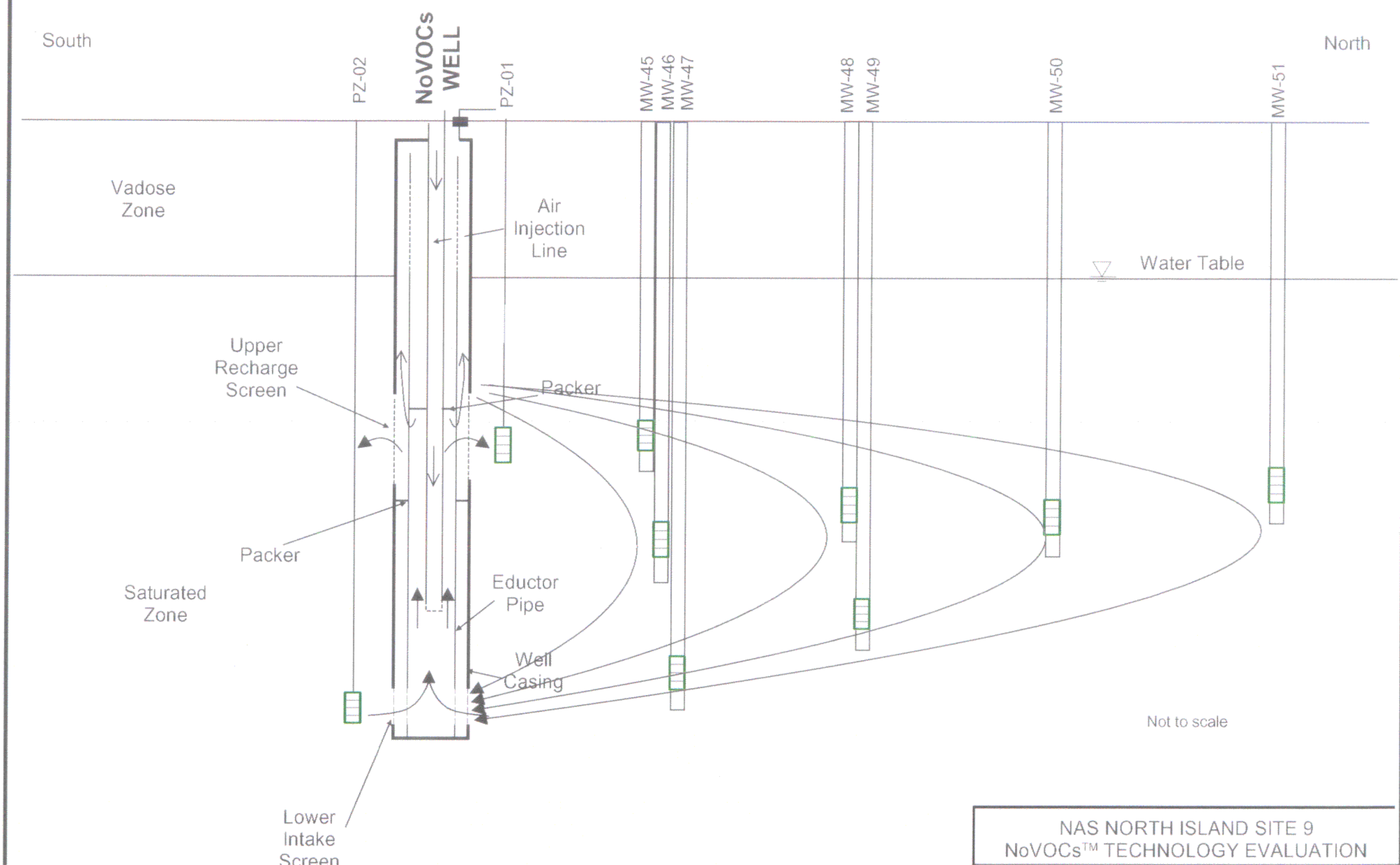


NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-2

WELL LOCATIONS

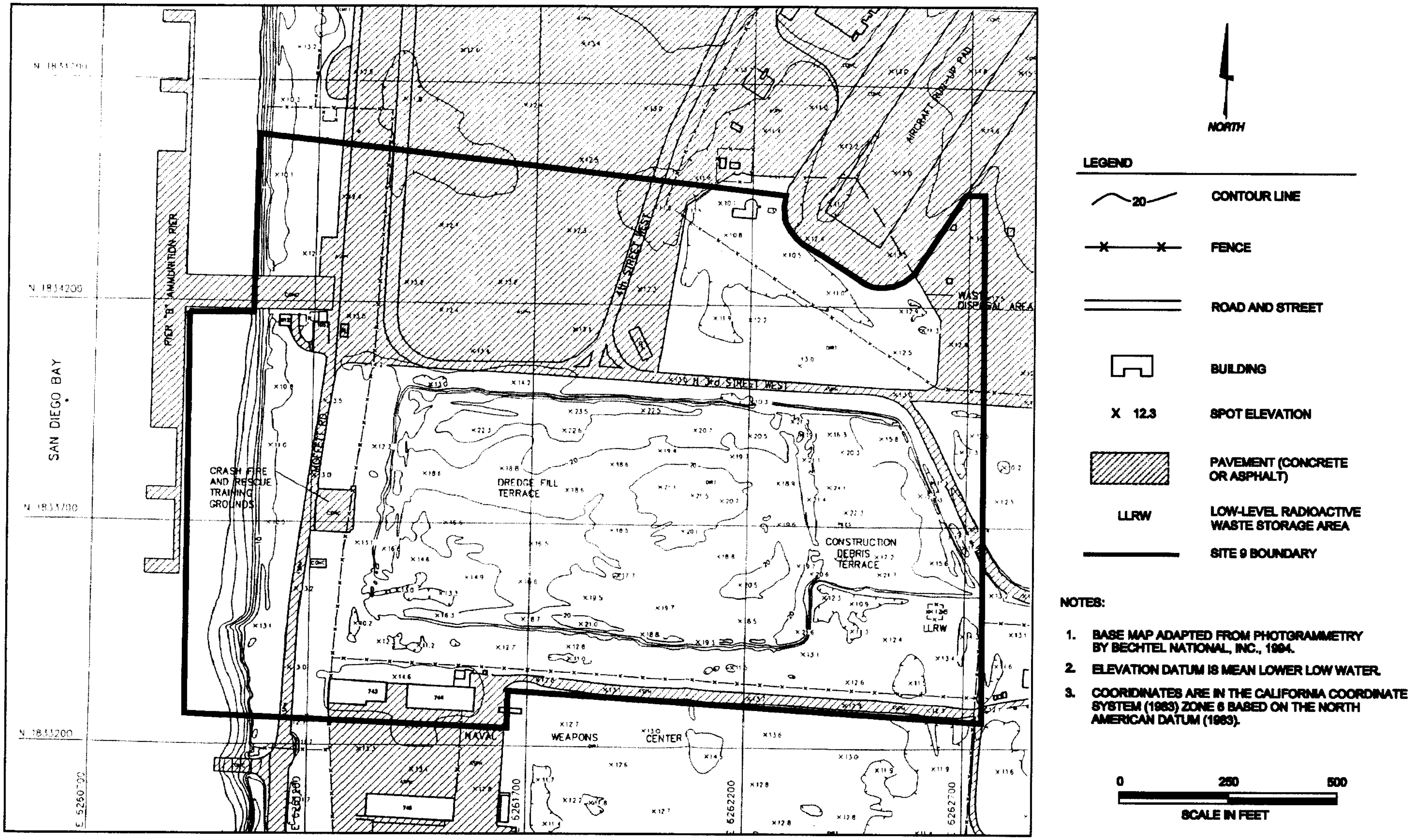
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ TECHNOLOGY EVALUATION

FIGURE 2-3
GENERALIZED CROSS-SECTION

Tetra Tech EM Inc.



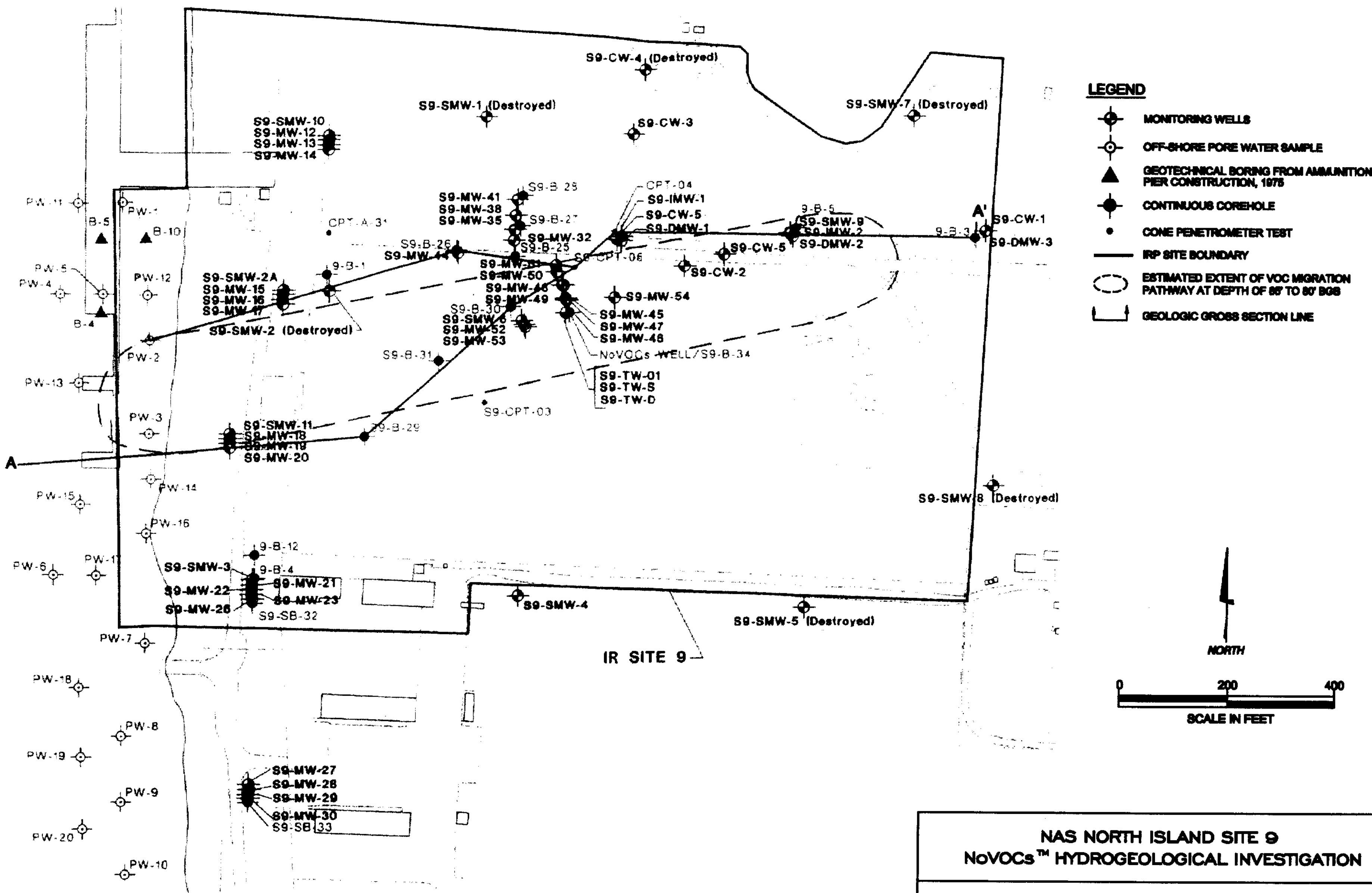
SOURCE: MODIFIED FROM JACOBS 1994

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-4

SITE 9 TOPOGRAPHIC ELEVATIONS

Tetra Tech EM Inc.



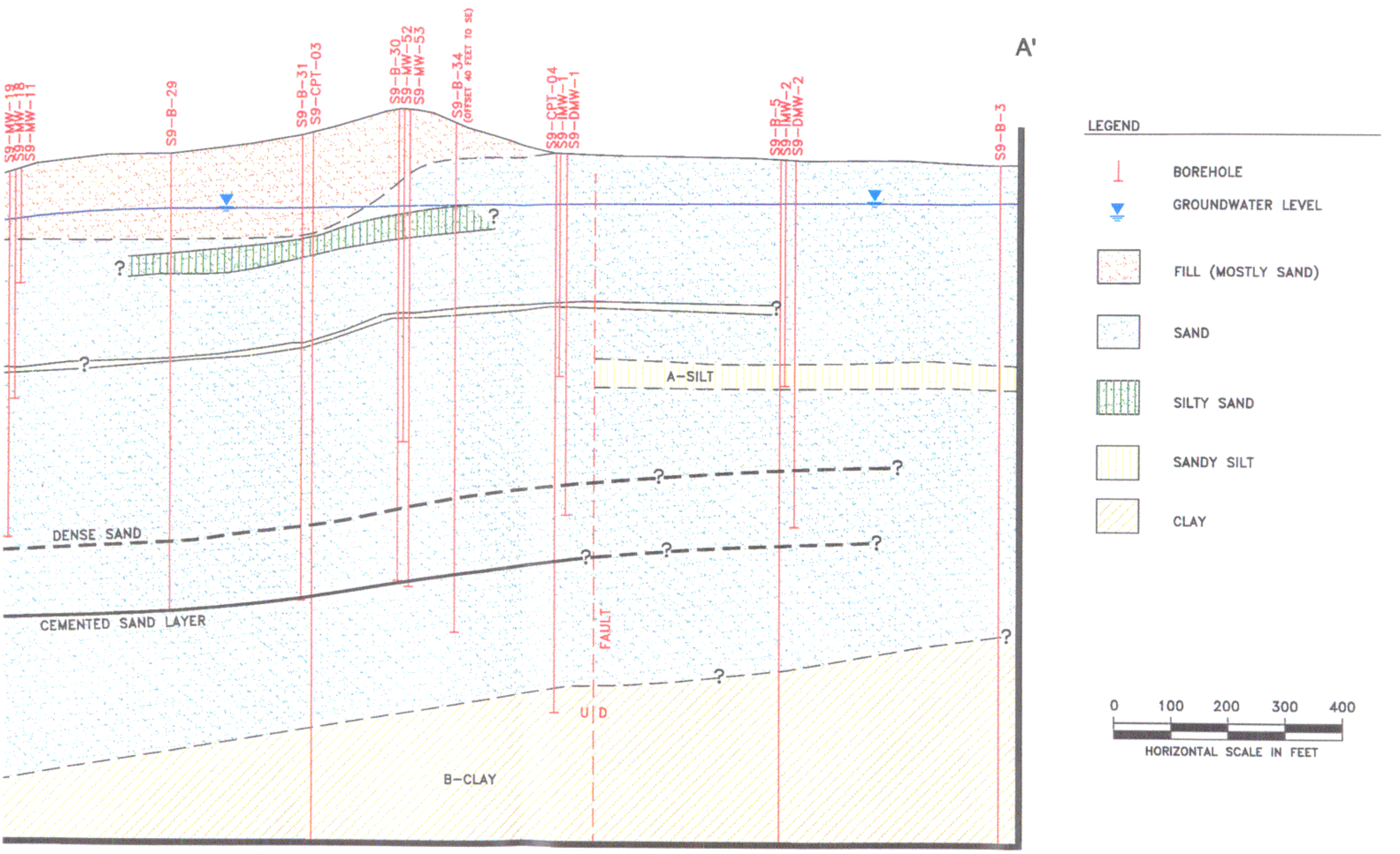
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-5

GEOLOGIC CROSS-SECTION LOCATION

Tetra Tech EM Inc.

SOURCE: MODIFIED FROM BECHTEL (1998)



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-6

GEOLOGIC CROSS SECTION A-A'

Tetra Tech EM Inc.

TABLE 2-1

WELL SCREEN INTERVALS
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Well	Description	Distance From NoVOCs™ Well (feet)	Screen Interval	
			Depth (feet bgs)	Elevation (feet relative to MLLW)
IW-01	NoVOCs™ well	0	43 to 47 and 72 to 78	-21.3 to -25.3 and -50.3 to -56.3
MW-45	Cross-gradient monitoring well	29.8	42 to 47	-20.0 to -25.0
MW-46	Cross-gradient monitoring well	27.7	57 to 62	-35.4 to -40.4
MW-47	Cross-gradient monitoring well	31.1	72 to 78	-49.9 to -55.9
MW-48	Cross-gradient monitoring well	61.9	52 to 57	-28.6 to -33.6
MW-49	Cross-gradient monitoring well	61.7	67 to 72	-43.6 to -48.6
MW-50	Cross-gradient monitoring well	90.7	52 to 57	-36.9 to -41.9
MW-51	Cross-gradient monitoring well	104.6	49 to 54	-35.1 to -40.1
MW-52	Downgradient monitoring well	93.0	41 to 46	-19.1 to -24.1
MW-53	Downgradient monitoring well	93.1	72 to 77	-50.4 to -55.4
MW-54	Upgradient monitoring well	107.9	38 to 78	-18.0 to -58.0

Notes:

bgs Below groundsurface

MLLW Mean lower low water level

3.0 TIDAL INFLUENCE STUDY

This section describes the configuration for and procedures of the tidal influence study and presents its results. The NoVOCs™ system began operation during the tidal influence study. The effects of NoVOCs™ system operation on groundwater levels is also discussed.

3.1 CONFIGURATION AND PROCEDURES

Tetra Tech conducted a tidal influence study from April 20 through 30, 1998 to measure natural fluctuations in water level at the site caused by tidal influences. Water level changes in the aquifer caused by NoVOCs™ system operation were also recorded because the system was started and shut down multiple times during the study period. Tetra Tech installed pressure transducers in nine observation wells in the immediate vicinity of the NoVOCs™ system and measured changes in water levels in the observation wells before system startup and during system operation. Measurements were collected before startup of the NoVOCs™ system to measure natural fluctuations in water levels at the site caused by tidal influences and to establish baseline groundwater elevation conditions. Water levels were measured during system startup and operation to assess the magnitude and extent of the water level changes caused by the NoVOCs™ system. This information was used to assist in evaluating the extent of the NoVOCs™ treatment cell.

To document water level changes in the aquifer caused by the NoVOCs™ system, Aquistar pressure transducers were installed in observation wells MW-45 though MW-53 (Figure 2-2). Transducers were not installed in piezometers PZ-01 and PZ-02 because the inner diameters of the piezometers were smaller than the outer diameter of the transducers. The installation of a transducer in observation well MW-54 was precluded by the presence of a multilevel diffusion sampler inside the well.

The pressure transducers had a ¾-inch outer diameter and were rated at 15 pounds per square inch (psi). All of the transducers are automatically compensated with barometric pressure changes (i.e., the pressure transducer readings are automatically adjusted to current atmosphere pressure). The transducers were installed approximately 6 feet below the water surface, and water level elevations were measured manually using an electronic water level sounder in each observation well immediately before the transducers were installed. Each transducer was connected to either a single- or multi-channel data logger. Before the transducers were installed, the data loggers were programmed to collect pressure readings every 10 minutes. The pressure readings are converted to feet of water above the transducer and

then to water level elevation. The transducers were used to collect groundwater elevation data from the observation wells from April 20 to 30, 1998. The transducers were removed from the observation wells on April 30, 1998. Water level readings were obtained with an electronic sounder before the transducers were removed to provide an additional accuracy check.

3.2 RESULTS

This section presents the results of the tidal influence study that was conducted to evaluate natural fluctuations in water levels at the site caused by tidal influences. The changes in water levels recorded in each of the observation wells were plotted versus time. These plots are presented in Appendix B. Figures B1 through B4 depict the fluctuations in water levels in the observation wells over the 10-day duration of the study. Figures B5 through B8 present the water levels in the observation wells for 12 hours of the first day of NoVOCs™ system operation. Figure B9 shows the water level fluctuation in San Diego Bay during the tidal study. The tidal influence and NoVOCs™ system influence are discussed separately in the following sections.

3.2.1 Tidal Influence

This section summarizes the effects of tidal influence on the groundwater levels. A detailed discussion of the analysis of the tidal influence study data is provided in Section 5.1.

Based on Figures B1 through B4, the water level readings follow a cyclical pattern in all observation wells included in the tidal study. Figures B1 through B4 illustrate the increase and decrease in groundwater levels caused by tidal fluctuations in San Diego Bay. Maximum groundwater level fluctuations measured in the observation wells ranged from 0.56 to 0.73 feet, depending on the location of the observation well. The amplitudes of the tidal fluctuations in water levels were highest for observation wells closest to San Diego Bay (MW-52 and MW-53). The other observation wells monitored during the tidal influence study (MW-45 through MW-51) are all located at approximately the same distance from San Diego Bay; the amplitudes of the tidal fluctuations in these wells are similar to one another.

The cyclical pattern of groundwater level fluctuation can be seen for all observation wells and correlates with published tide charts for San Diego Bay with a time lag ranging from approximately 46 to 96 minutes, depending on observation well location and magnitude of the tidal fluctuation. The time lag also depends on the degree of hydraulic communication between the bay and the wells. The range of time

lags is similar for each of the observation wells because of the similar distance relative to San Diego Bay. The aquifer zone is generally in good hydraulic communication with the San Diego Bay.

3.2.2 NoVOCs™ System Influence

Figures B5 through B8 show groundwater elevations during approximately 12 hours of the first day of the study that included several NoVOCs™ system startups and shutdowns. Table 3-1 lists the start and stop times for the NoVOCs™ system on April 20, 21, and 22, 1998, as reported by the Navy. Groundwater level changes caused by startup and shutdown of the NoVOCs™ system on April 20, 1998, are evident in the water level data for well cluster MW-45, MW-46, and MW-47, located approximately 30 feet from the NoVOCs™ well (Figure B5). The water level data for observation wells MW-45 (the upper screened well in this cluster) and MW-46 (intermediate screened well) show water level increases after system startup. The groundwater elevation increase in well MW-45 was approximately 0.15 foot of water. Observation well MW-46, the intermediate depth well, shows a water level increase of approximately 0.05 foot of water. Observation well MW-47, the deep screened well, shows a water level decrease of approximately 0.025 foot. This pattern of water level increases and decreases associated with the operation of the NoVOCs™ system is expected based on the monitoring well screen locations relative to the NoVOCs™ well screen locations. The deep screened well experiences a drop in water level as water is drawn toward the NoVOCs™ well intake, and the upper screened wells experience increases in water level as water is lifted inside the NoVOCs™ well, and discharges into the upper aquifer. In well pair MW-48 and MW-49 (located approximately 62 feet from the NoVOCs™ well) and in wells MW-50 and MW-51 (located approximately 91 and 105 feet, respectively, from the NoVOCs™ well), water level changes associated with NoVOCs™ system operation are not apparent (Figures B6, B7, and B8).

TABLE 3-1

START AND STOP TIMES FOR THE NoVOCs™ SYSTEM
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Date	Time[a]	Action
April 20, 1998	10:01	Start
	10:01	Stop
	10:04	Start
	10:05	Stop
	10:18	Start
	10:24	Stop
	15:54	Start
	16:20	Stop
	18:08	Start
	18:32	Stop
	18:50	Start
	18:51	Stop
	18:56	Start
	19:00	Stop
	19:10	Start
April 21, 1998	16:20	Stop
	16:23	Start
	16:40	Stop
	18:45	Start
April 22, 1998	12:30	Stop
	13:03	Start
	13:12	Stop
	13:40	Start
	14:01 through 14:19	Six stop and start cycles to check auto shutdown functions
	14:19	Start (system in continuous operation)

Note:

a Rounded to nearest minute

4.0 AQUIFER TESTING

A series of aquifer tests were conducted at the demonstration site from July 27 through August 5, 1998, to obtain information on hydraulic communication between various portions of the aquifer beneath the site, as well as data for estimating values of aquifer hydraulic parameters such as hydraulic conductivity, transmissivity, storativity, and anisotropy. In addition, the aquifer tests were conducted to obtain data for calculating well efficiencies for the two screened intervals of the NoVOCs™ well.

Aquifer testing was conducted using the NoVOCs™ well (IW-01) as the pumping or injection well. Two piezometers and 10 observation wells were available for water level measurements. An inflatable packer was used to isolate the two screened intervals within the NoVOCs™ well to allow pumping from each screened interval separately. The aquifer tests, in the order conducted, were as follows:

- Step drawdown test in the upper screened interval conducted on July 27, 1998
- A 32-hour constant discharge pumping test in the upper screened interval conducted on July 28 and 29, 1998
- Injection test in the upper screened interval conducted on July 31, 1998
- Step drawdown test in the lower screened interval conducted on August 1, 1998
- Dipole flow test with pumping in the lower screened interval and injection in the upper screened interval conducted on August 5, 1998

A constant discharge pumping test for the lower screened interval was not conducted because of the excessive volume of water that would be generated and the prohibitive cost of water disposal.

4.1 PRETESTING ACTIVITIES

Before initiating the aquifer tests, certain downwell components of the NoVOCs™ system were removed, the well screens and filter pack were redeveloped, and aquifer testing equipment was installed. A description of each pretesting activity is provided in the following subsections.

4.1.1 NoVOCs™ Equipment Removal

To allow access for aquifer testing equipment, downwell components of the NoVOCs™ system were removed, except for the 8-inch diameter outer casing and the prepacked screen on the eductor casing at 72 to 78 feet bgs (-50.4 to -58.0 feet MLLW). In addition, piezometers, PZ-01 and PZ-02, set in the filter pack adjacent to the intake and recharge screens of the NoVOCs™ well, were not removed and were used as monitoring points during the aquifer tests. The downhole components removed included the 5-inch, schedule 40 polyvinyl chloride (PVC) eductor casing, the 2-inch PVC airline and diffuser, all packers, and downhole probes and meters.

4.1.2 Video Survey and Well Screen Development

To assess the condition of the NoVOCs™ well screens, a downhole video camera was lowered into the well to visually inspect the condition of the well casing and well screens. Two downwell video surveys of the NoVOCs™ well were conducted: one after internal NoVOCs™ well components were removed, and the other after well redevelopment and cleaning of the well screens. The camera was lowered on a taped cable so that the depth of the camera was known. The camera was capable of rotating up to 360 degrees on command. During the initial video survey, heavy orange iron staining on the well casing and well screens was observed. In addition, excessive orange iron flocculant was observed in the water column along with orange iron bioslime in the well screen intervals. Orange iron precipitant was also observed on the eductor pipe, eductor screen, and air line during removal of the internal well components. These observations suggest that iron precipitation and microbiological growth in the well are occurring. Both of these factors may impair the performance of the NoVOCs™ system by obstructing the well screen and filter pack material. Groundwater samples collected from the well by MACTEC confirmed that microorganisms were present in the NoVOCs™ well at high levels (Personal Communication from Scott Donovan, Bechtel 1998).

To remove the microbiological growth and precipitant, the well was redeveloped using surge and pump methods and hydrochloric acid was added to the well water. Approximately 2.5 gallons of hydrochloric acid were tremmied into the upper and lower screen intervals of the NoVOCs™ well, and the well water was agitated for a period 30 minutes. After cleaning the NoVOCs™ well screens with acid, the video camera was lowered into the well a second time to evaluate the effectiveness of well cleaning and development.

The second video survey showed that redevelopment and cleaning were effective in removing precipitant and microbiological growth in the well screens. In addition, the orange iron flocculant was removed from the water column within the well. Review of the integrity of the well casing during the second survey indicated that the well was intact with no signs of damage. However, a manufacturing defect in the upper well screen was observed. The screen slots in the upper well screen are unevenly cut, and about 30 percent of the slots do not completely penetrate the PVC casing. This defect limits the efficiency of the upper screen interval and may reduce the available water level rise in the NoVOCs™ well during recharge into the aquifer through the upper screen interval.

4.1.3 Aquifer Test Equipment Installation and Configuration

The first set of aquifer tests were conducted in the upper screened interval of the NoVOCs™ well and consisted of step drawdown, constant discharge, and injection tests. The second set of aquifer tests were conducted in the lower screened interval of the NoVOCs™ well and consisted of step drawdown and dipole flow tests. This section describes installation and configuration of aquifer testing equipment.

Pump and Packer

Pumping equipment configuration was identical for the step drawdown test and constant discharge pumping test conducted in the upper screened interval (Figures 4-1 and 4-2). To pump only the upper screened interval of the NoVOCs™ well, the two screened intervals were hydraulically separated using a 5-inch-diameter by 5-foot-long inflatable Baski packer. The inflatable packer was set between the two screened intervals at a depth of approximately 62 to 67 feet bgs (-40.3 to -45.3 feet MLLW). The pump used for the aquifer tests was a 4-inch stainless steel Grundfos submersible pump with a capacity of 100 gallons per minute. The pump was installed above the packer with its intake at approximately 55 feet bgs (-33.3 feet MLLW). The pump and the packer system were set in the NoVOCs™ well using a 2-inch diameter steel drop pipe (Figure 4-1). The drop pipe was secured at the well head and connected to a 2-inch diameter PVC discharge line. After the pump was set, the packer was inflated to a pressure of 70 pounds per square inch using a pressurized nitrogen cylinder. The packer's pressure was monitored throughout the pumping tests at the well head using a pressure gauge. The same equipment was used for the stepdrawdown and dipole flow tests conducted in the lower screened interval of the NoVOCs™ well (Figures 4-4 and 4-5). The packer was installed at approximately 56 to 61 feet bgs (-34.3 to -39.3 feet MLLW) and the submersible pump was set immediately below the packer at approximately 65 feet bgs (-43.3 feet MLLW).

Pressure Transducers and Data Loggers

Pressure transducers manufactured by AquiStar were installed in observation wells MW-45 through MW-54 and in the pumping well (one transducer above the packer system and one transducer below the packer). The pressure transducers used were pressure rated between 5 and 30 psi. The higher pressure rating transducers were installed in wells anticipated to exhibit the greatest change in water level (observation wells MW-45 through MW-49 and the pumping well). Transducers with pressure ratings of 5 psi were installed in observation wells farthest from the NoVOCs™ well (MW-50 through MW-54) because smaller changes in water levels were expected during the pumping tests.

The transducers were connected to single- and multi-channel data loggers. The pressure readings by the transducers were automatically adjusted to the atmosphere pressure so that no barometric pressure correction is needed for the pressure/water level readings by the transducers. In addtion, barometric efficiency was expected to be low for the testing aquifer under unconfined condition. Therefore, barometric efficiency was not calculated and barometric pressure correction for observed water levels was not conducted.

During transducer installation, the depth to groundwater was measured with an electronic water level sounder before lowering the transducer into the well. The pressure transducer was then connected to the data logger and the transducer was lowered into the well. The transducer was set at a depth so that it would remain submerged during the pumping test at a depth below water not exceeding the pressure rating of the transducer. The pressure transducer cable was secured to the well head and the surface using duct tape, so that no movement occurred during the pumping test. After the transducer was secured, a reading of the length of the column of water above the transducer was recorded.

During the aquifer tests, the data loggers for the NoVOC™ well and observation wells MW-45, MW-46, and MW-47 were constantly connected to a laptop computer to view recorded data. Data loggers for observation wells MW-48 through MW-54 were periodically connected to a laptop to confirm that water level readings were being recorded properly. In addition, transducer data were periodically checked by collecting water level measurements using an electronic water level sounder.

Other Equipment

During the aquifer tests, the pumping and injection rates were regulated using a variable rate controller, a flow control valve, and two inline flow meters. The flow meters used were a McCrometer electronic flow meter with totalizer and a Precision flow meter with totalizer. The meters were installed on the discharge pipe at the well head. The flow meters were calibrated in the field by measuring the time required to fill a 5-gallon bucket with water pumped through the discharge line.

All water generated during the pumping tests was piped to on-site storage tanks to await chemical characterization and subsequent disposal. To accommodate the volume of water generated during the pumping tests, four 20,000-gallon tanks were staged on site for storage of the extracted groundwater. Water quality parameters including pH, oxidation and reduction potential, specific conductance, temperature, and dissolved oxygen were measured during development and removal of the well water. Horiba U10 and YSI 2000 water quality meters were used to measure the water quality parameters in the field. The instruments were calibrated daily in accordance with the manufacturer's instructions.

4.1.4 Data Logger Programming

The data loggers were programmed using the length of the column of water above the transducer, depth of water below the top of well casing, and the survey elevation on the top of the casing so that subsequent readings were relative to MLLW. The data loggers were programmed for each pumping test to collect data at specific times and frequencies. Because of significant water level responses to changes in pumping rate (including starting and stopping pumping), the data loggers for the NoVOCs™ well and observation wells MW-45 through MW-47 were programmed to collect data at a higher frequency immediately following any change in pumping rate. The programmed data collection schedule was as follows: every half-second for 20 readings, every second for 50 readings, every 2 seconds for 60 readings, every 5 seconds for 60 readings, every 10 seconds for 30 readings, every minute for 20 readings, every 2 minutes for 20 readings, every 5 minutes for 12 readings, every 10 minutes for 18 readings, and every 20 minutes for 500 readings. (This schedule was reinitiated following any change in pumping rate and was generally terminated before the last step reached completion.) Collecting water level measurements in this manner provided data at higher frequencies when the rate of water level change was greater. Data loggers for observation wells MW-48 through MW-54 were programmed to collect data at lower frequencies, typically once per minute. All data were downloaded from the data logger to a computer and the data logger was reset between each aquifer test.

4.2 STEP DRAWDOWN TEST OF THE UPPER SCREENED INTERVAL

Tetra Tech conducted a step drawdown test in the upper screened interval of the NoVOCs™ well to estimate the optimal pumping rate for a constant discharge pumping test, and to estimate the well efficiency and specific capacity of the upper screened interval of the NoVOCs™ well. Test procedures and results are discussed below.

4.2.1 Procedures

On July 22, 1998, Tetra Tech conducted an initial step drawdown test on the upper screened interval of the NoVOCs™ well to estimate the optimal pumping rate for a constant discharge pumping test and the well efficiency and specific capacity of the upper screened interval of NoVOCs™ well. The step drawdown test was conducted by separating the upper and lower screened sections of the NoVOCs™ well using a packer system and pumping the upper screened interval of the well with a submersible pump (Figure 4-1), as described in Section 4.1.3. Based on observations of water levels in the recharge and intake piezometers (PZ-01 and PZ-02), the integrity of the inflatable packer seal between the upper and lower screens was determined to have been compromised during the initial test.

A second step drawdown test in the upper screened interval of the NoVOCs™ well was conducted on July 27, 1998. During the second test, water was first pumped at a rate of 43 gpm for about 17 minutes to check the integrity of the packer system. The water level in piezometers PZ-01 and PZ-02 remained stable during pumping of the upper screened interval, indicating that the packer seal was effective. Water was then pumped at 10 gpm for 11 minutes, 15 gpm for 45 minutes, and 20 gpm for 45 minutes. Water levels in the NoVOCs™ well and the surrounding observation wells were monitored using pressure transducers to measure changes in water level within the aquifer. A summary of the step drawdown test for the upper screen interval of the NoVOCs™ well is provided in Table 4-1.

4.2.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well (upper and lower intervals) and observation wells MW-45 through MW-54 are presented in Appendix C as Figures C1 through C7. Results for observation well MW-49 are not available because of a data logger malfunction.

Decreases in water levels were recorded in the pumping well (Figure C1) and observation wells MW-45 through MW-54 (Figures C2 through C7). The water level changes in the pumping well and observation wells exhibited similar patterns in response to changes in pumping rate; however, the responses decreased with distance from the NoVOCs™ well and with depth of the observation wells. When pumping at 20 gpm, the pumping well exhibited a maximum water level decrease of about 14 feet; observation well MW-45 (approximately 30 feet from the pumping well) showed a water level decrease of 0.6 foot; and observation well MW-51 (about 105 feet from the pumping well), showed a water level decrease of about 0.03 foot. The observation wells exhibited an almost immediate response to changes in pumping rate, suggesting that the aquifer has good communication in both the horizontal and vertical directions.

4.3 CONSTANT DISCHARGE PUMPING TEST OF THE UPPER SCREENED INTERVAL

A constant discharge pumping test in the upper screened interval was conducted following the step drawdown test in the upper screened interval of the NoVOCs™ well and following complete water level recovery in the pumping well, the observation piezometer, and the observation wells. Constant discharge pumping test procedures and results are discussed below.

4.3.1 Procedures

Based on the results of the step drawdown test (Section 4.2.2), 20 gpm was selected as the pumping rate for the constant discharge pumping test in the upper screening interval of the NoVOCs™ well. On July 28 through 30, 1998, Tetra Tech conducted a constant discharge pumping test to estimate the hydraulic conductivity, transmissivity, storativity, and anisotropy of the shallow aquifer. The constant discharge pumping test was conducted by isolating the upper and lower screened intervals of the NoVOCs™ well using a packer system and pumping the upper screened interval of the well with a submersible pump (Figure 4-2), as described in Section 4.1.3. Water was pumped at a constant discharge of 20 gpm for about 32 hours. Afterward, recovery data from the pumping well and the observation wells were collected for 24 hours. Recovery rates were recorded in the pumping well and all observation piezometers and wells. Pumping equipment remained in the pumping well until recovery monitoring was complete. Water levels in the NoVOCs™ well and the surrounding observation wells were monitored using pressure transducers to measure changes in water level within the aquifer. A summary of the constant discharge pumping test for the upper screened interval of the NoVOCs™ well is provided in Table 4-2.

4.3.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well and observation wells MW-45 through MW-54 are presented in Appendix D as Figures D1 through D6. Results for observation well MW-50 are not available because of a data logger malfunction.

Drawdown in the pumping well was measured at about 16 feet. With the exception of the pumping well, changes in water levels in the observation wells are difficult to discern without tidal corrections to determine actual drawdown. Tidal corrections for the constant discharge pumping test data are discussed and applied in Section 5.1.

4.4 INJECTION TEST OF THE UPPER SCREENED INTERVAL

The pumping equipment used for the step drawdown and constant discharge pumping tests were left in the well for the injection test in the upper screened interval. Injection test procedures and results are discussed below.

4.4.1 Procedures

The injection test was conducted in the NoVOCs™ well by injecting a constant rate of potable water through the upper screened interval of the NoVOCs™ well. Clean tap water was brought to the site using a fire hose and was stored adjacent to the NoVOCs™ well in a 300-gallon holding tank. Water was initially introduced to the NoVOCs™ well by gravity flow from the holding tank to the NoVOCs™ well. Water flow rates were controlled by a flow valve and were measured using an inline flow meter and totalizer. Flow rate was monitored closely so that a constant flow rate was injected. On July 30, 1998, approximately 1.5 hours after starting the injection test, water injection was terminated because particulate material was observed in the tap water being injected into the NoVOCs™ well. The particulate material was identified as scaling from the hose used to transport the potable water. Approximately 1,200 gallons of water had been injected during the initial injection test. To remove the particulate material injected, approximately 6,000 gallons of water was pumped from the upper screened interval of the NoVOCs™ well. To eliminate the particulate problem, the water storage tank was eliminated and a new fire hose was plumbed directly to the NoVOCs™ well through a flow control value and inline flow meter (Figure 4-3). Before reinitiating water injection, the aquifer was allowed to stabilize overnight.

On July 31, 1998 through August 1, 1998, Tetra Tech conducted an injection test to obtain information on the recharge capacity and specific capacity of the upper screened interval of the NoVOCs™ well. Potable water was injected at rates of 5, 15, and 22 gpm for a period of about 1 hour at each rate. Potable water was also injected at a rate of 30 gpm for 4 minutes and 25 gpm for about 14 minutes. Based on the water injection rate and duration, a total of approximately 3,000 gallons of water was injected into the aquifer during the injection test. After water injection was stopped, water levels continued to be monitored for approximately 14 hours of recovery. A summary of the injection test for the upper screened interval of the NoVOCs™ well is provided in Table 4-3.

4.4.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well (upper and lower intervals), and observation wells MW-45 through MW-54 are presented in Appendix E as Figures E1 through E7. An increase in water level was recorded in the injection well and in observation wells MW-45 through MW-54. The water levels in the injection well and observation wells exhibited similar patterns in response to changes in pumping rate; however, the response decreased with distance from the NoVOCs™ well and with depth of the observation wells. The upper screened interval recharged clean tap water at a flow rate of 22 gpm for 1 hour with a 14.4 foot increase in water level. When the flow rate was increased to 30 gpm, the water level quickly increased another 3.6 feet to about 18 feet above the initial water level and began discharging at the ground surface. The injection rate was decreased to 25 gpm for about 15 minutes, during which groundwater elevations stabilized at about 17 feet above the initial water level. This information shows that the upper well screen can recharge clean tap water at an injection rate near the design pumping rate of the NoVOCs™ system (25 gpm). However, the injection rates were run for only 1 hour each and, therefore, the corresponding increase in water level may not represent complete stabilization of the aquifer.

4.5 STEP DRAWDOWN TEST OF THE LOWER SCREENED INTERVAL

After the injection test was completed and the aquifer had recovered, the pumping equipment was reconfigured for aquifer testing of the lower screened interval of the NoVOCs™ well (72 to 78 feet bgs). The procedures for and results of the step drawdown test of the lower screened interval are discussed below.

4.5.1 Procedures

On August 1 and 2, 1998, Tetra Tech conducted a step drawdown test to assess the well efficiency and specific capacity of the lower screened interval of the NoVOCs™ well. The step drawdown test was conducted by separating the upper and lower screened intervals of the NoVOCs™ well using a packer system and pumping the lower screened interval of the well with a submersible pump (Figure 4-4), as described in Section 4.1.3. Water was first pumped at a rate of 40 gpm for 10 minutes to check the integrity of the packer system. Water was then pumped at rates of 50, 64, and 30 gpm for a period of about 1 hour at each rate. After pumping stopped, water levels continued to be monitored for approximately 13 hours of recovery. A summary of the step drawdown test for the lower screened interval of the NoVOCs™ well is provided in Table 4-4.

4.5.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well (upper and lower intervals) and observation wells MW-45 through MW-54 are presented in Appendix F as Figures F1 through F7. Results for observation well MW-50 are not available because of data logger malfunction. A decrease in water level was recorded in the pumping well and observation wells MW45 through MW54. The water levels in the pumping well and observation wells exhibited similar patterns in responses to changes in pumping rate; however, the responses decreased with distance away from the NoVOCs™ well and with depth of the observation wells. A drawdown of greater than 20 feet was observed in the lower screened interval of the pumping well. The observation wells exhibited an almost immediate response to changes in pumping rate, suggesting that the aquifer has good communication in both the horizontal and vertical directions.

4.6 DIPOLE FLOW TEST

After the aquifer had recovered from the step drawdown test of the lower screened interval, the pumping discharge line was redirected to inject pumped water through the upper screened interval. The procedures for and results of the dipole flow test are discussed below.

4.6.1 Configuration and Procedures

On August 5 through 7, 1998, Tetra Tech conducted a dipole flow aquifer test (simultaneous pumping and injection of groundwater) to investigate groundwater circulation through the NoVOCs™ system and to calibrate the downhole inline flow meter. The dipole flow test was conducted by pumping a constant rate of groundwater from the lower screened section of the NoVOCs™ well and injecting groundwater into the upper screened section of the NoVOCs™ well (Figure 4-5). Groundwater was pumped and injected at rates of 5, 10, 15, 20, and 25 gpm for periods ranging from 54 to 71 minutes for each rate. Pumping and injection flow rates were measured using an inline flow meter. Flow measurement was also attempted using an orifice plate (the same orifice plate used in the NoVOCs™ well); however, the magnahelic used to measure pressure across the orifice plate was damaged during the test and reliable measurements could not be collected. Instead, pumping and injection flow rates were measured using an inline flow meter. A total of approximately 4,600 gallons of water were pumped and injected during the dipole flow test. A summary of the dipole flow test for the upper and lower screened sections of the NoVOCs™ well is provided in Table 4-5.

4.6.2 Results

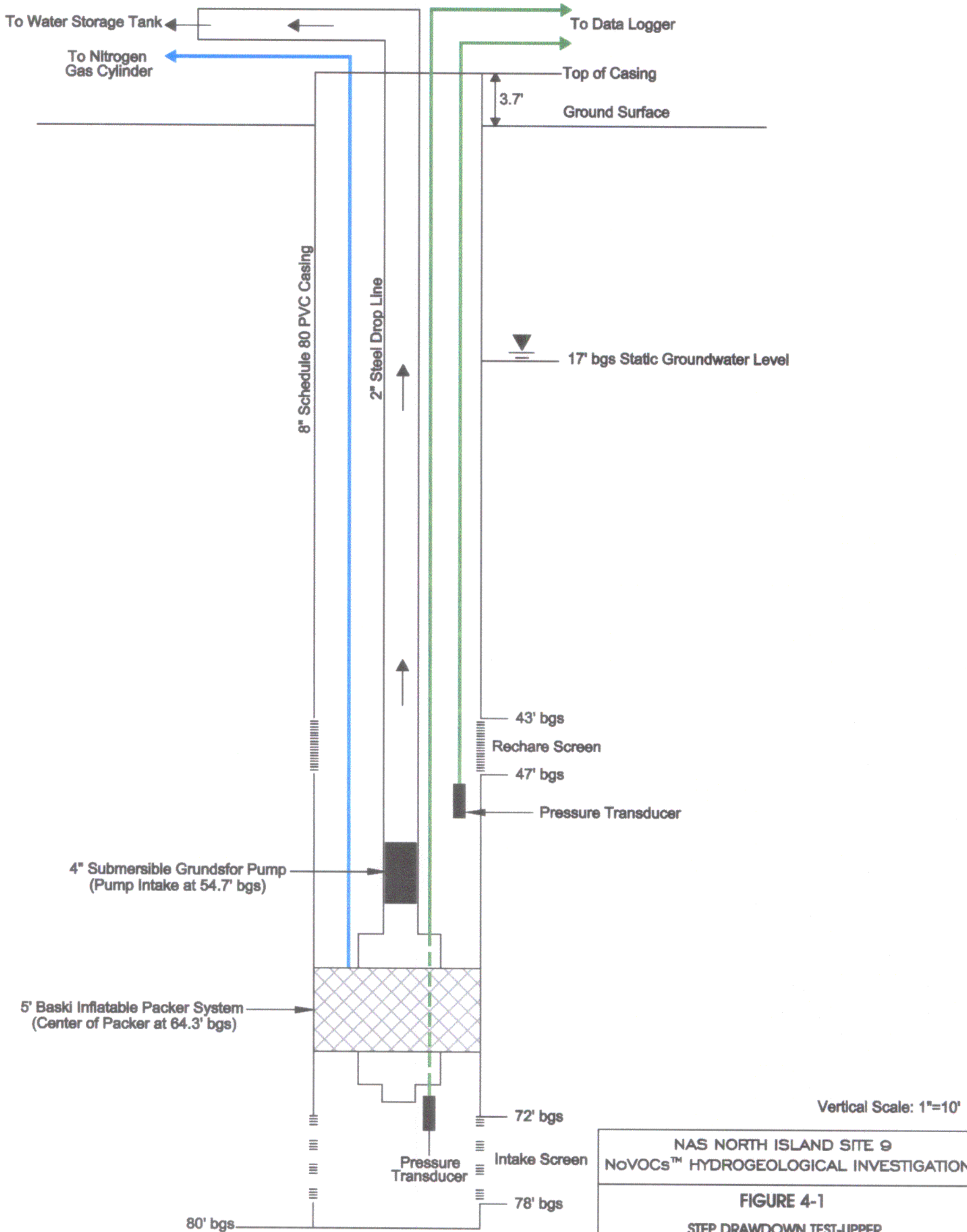
Dipole flow test data are presented in Appendix G. Figure G-1(Appendix G) shows pressure transducer data for the pumping and recharge intervals of the NoVOCs™ well. Hand measurements of water level rise at the upper recharge interval are also plotted. Drawdown data for the pumping interval show that the water level changed quickly and approached a steady state in a very short time. The drawdown recovery was just as rapid after the pump was turned off. This type of drawdown response makes analysis of transient state data difficult or impossible. In the other hand, water level rise data for the recharge interval show a longer transient stage at the beginning of each test step.

Pressure transducer and hand measurement data collected from the observation wells are presented in Figures G2 through G6 (Appendix G). As shown in Figure G2, well MW-45 shows a small water level rise during each step of the dipole flow test. In wells MW-46 and MW-47, some pressure response can be identified at the beginning of each step, but drawdown or water level rise cannot be positively measured at these two wells. Observation wells MW-48, MW-49, MW-51, MW52, MW53, and MW-54 showed very little or no response to the dipole flow test.

4.7 WATER QUALITY PARAMETERS

Water quality parameters including temperature, specific conductance, pH, reduction/oxidation potential, dissolved oxygen, salinity, and turbidity were measured in water from the pump discharge line during the pumping tests. A summary of the water quality parameter measurements is provided in Table 4-6. In general, results for the water quality parameters are higher in the lower screened zone, with the exception of pH and temperature. This finding is also supported by VOC concentration data from the wells at the demonstration site, which exhibit higher concentrations in samples from the deep wells than in samples from the shallow wells.

Specific conductance and salinity values measured during pumping of the upper screened interval averaged 22.2 micromhos per centimeter (μmhos/cm) and 2.26 percent, respectively, while the same parameters measured during pumping of the lower screen interval averaged 27.4 μmhos/cm and 2.71 percent. These results are consistent with the range of values and trend toward increased specific conductance and salinity with depth. Average temperature measured while pumping the upper and lower screened intervals was about 21.7 °C. Results of pH measurements while pumping the upper screened interval averaged 7.40, which was higher than the average pH value of 7.03 calculated from measurements collected when pumping the lower screened interval. The average reduction/oxidation potential in the upper interval was 22.7 millivolts (mv), while the average reduction/oxidation potential (Eh) in the lower interval was minus 30.5 mv. Dissolved oxygen concentrations also increased from an average of 7.92 milligrams per liter (mg/L) in the upper screened interval to 8.27 mg/L in the lower screened interval. Because the packer seal was not set appropriately during the July 22, 1998, step drawdown test in the upper screened interval, water quality measurements from the test were not used in calculating average water quality values.



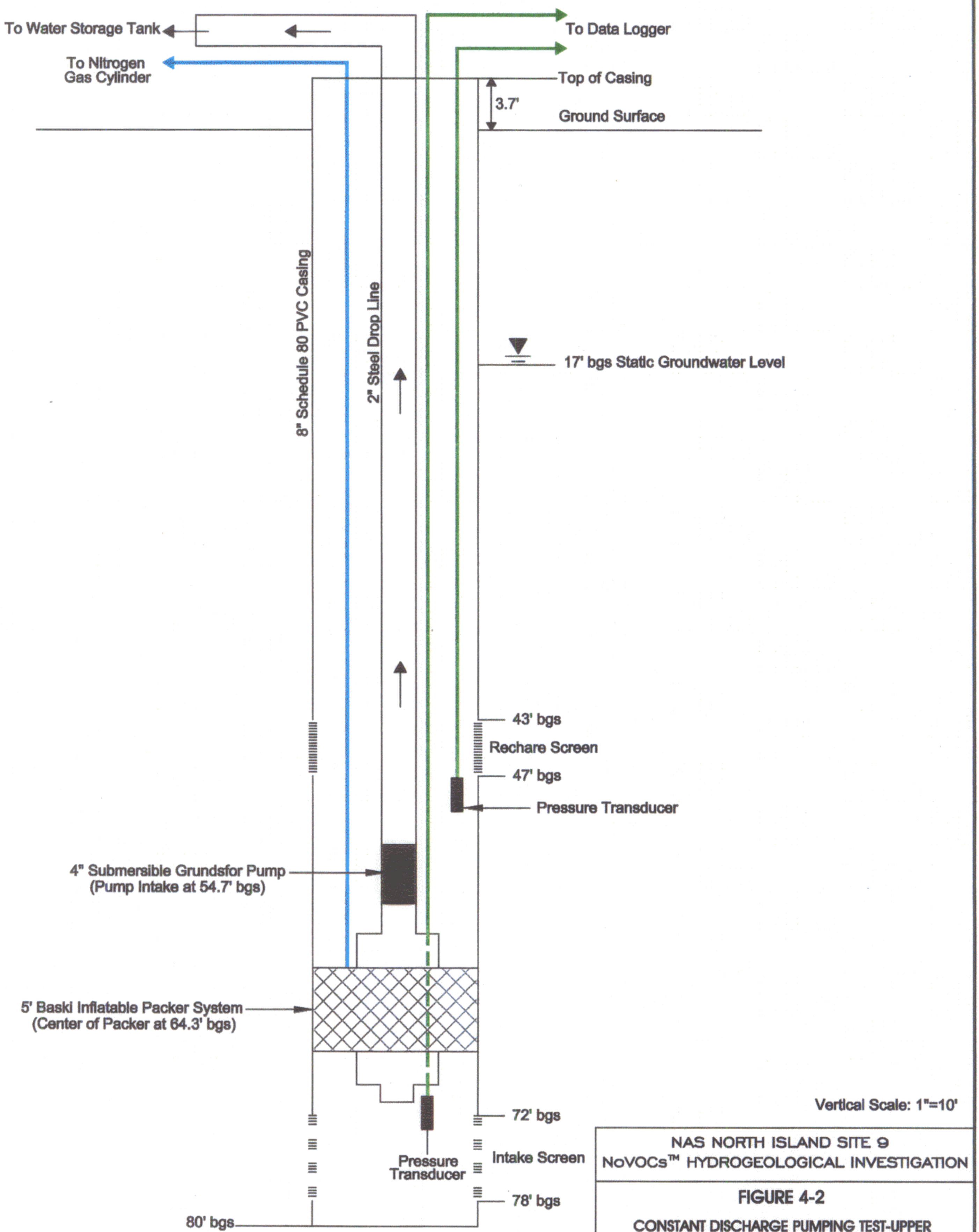
Vertical Scale: 1"=10'

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-1

STEP DRAWDOWN TEST-UPPER
SCREENED INTERVAL PUMPING WELL CONFIGURATION

Tetra Tech EM Inc.

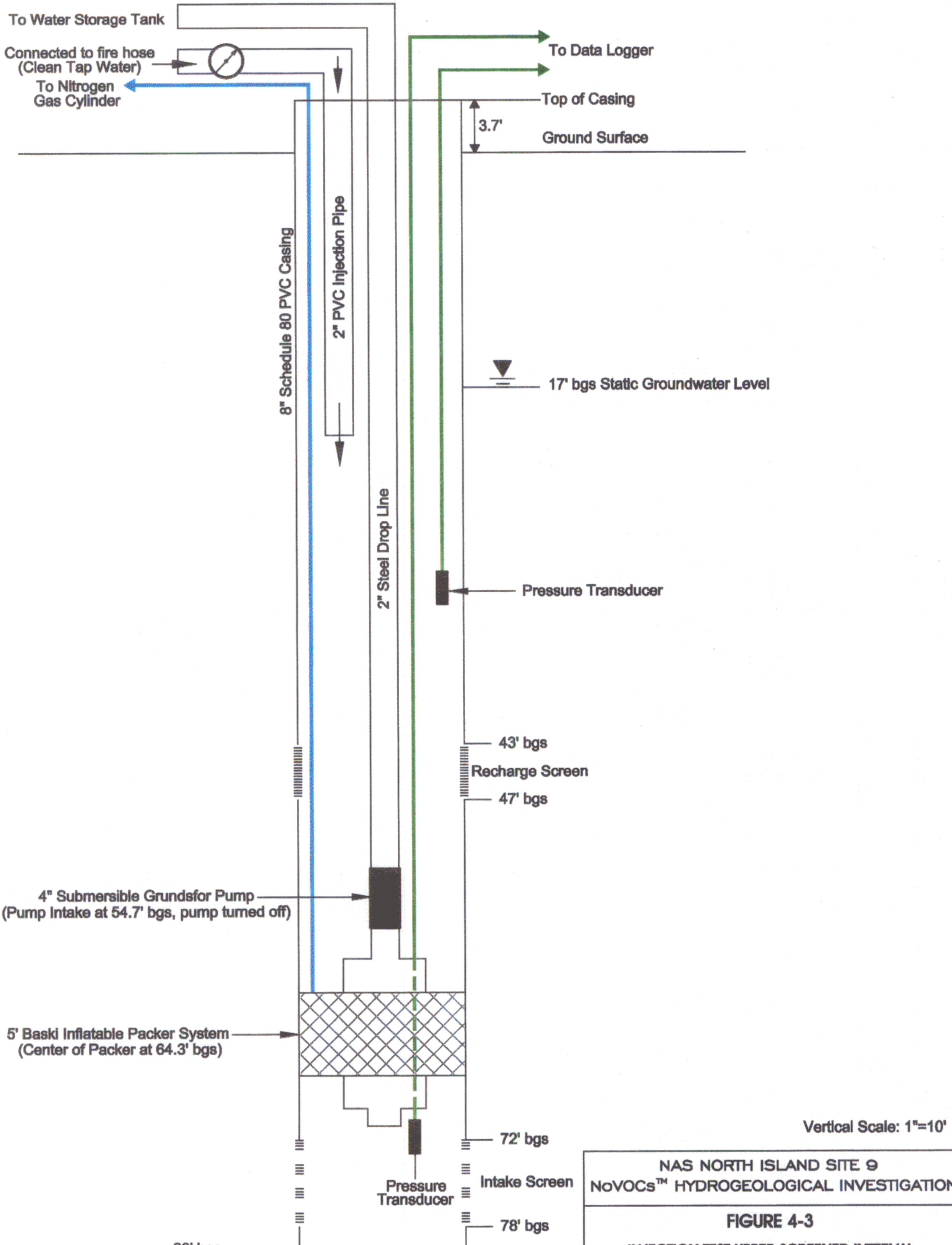


NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-2

CONSTANT DISCHARGE PUMPING TEST-UPPER SCREENED INTERVAL PUMPING WELL CONFIGURATION

Tetra Tech EM Inc.

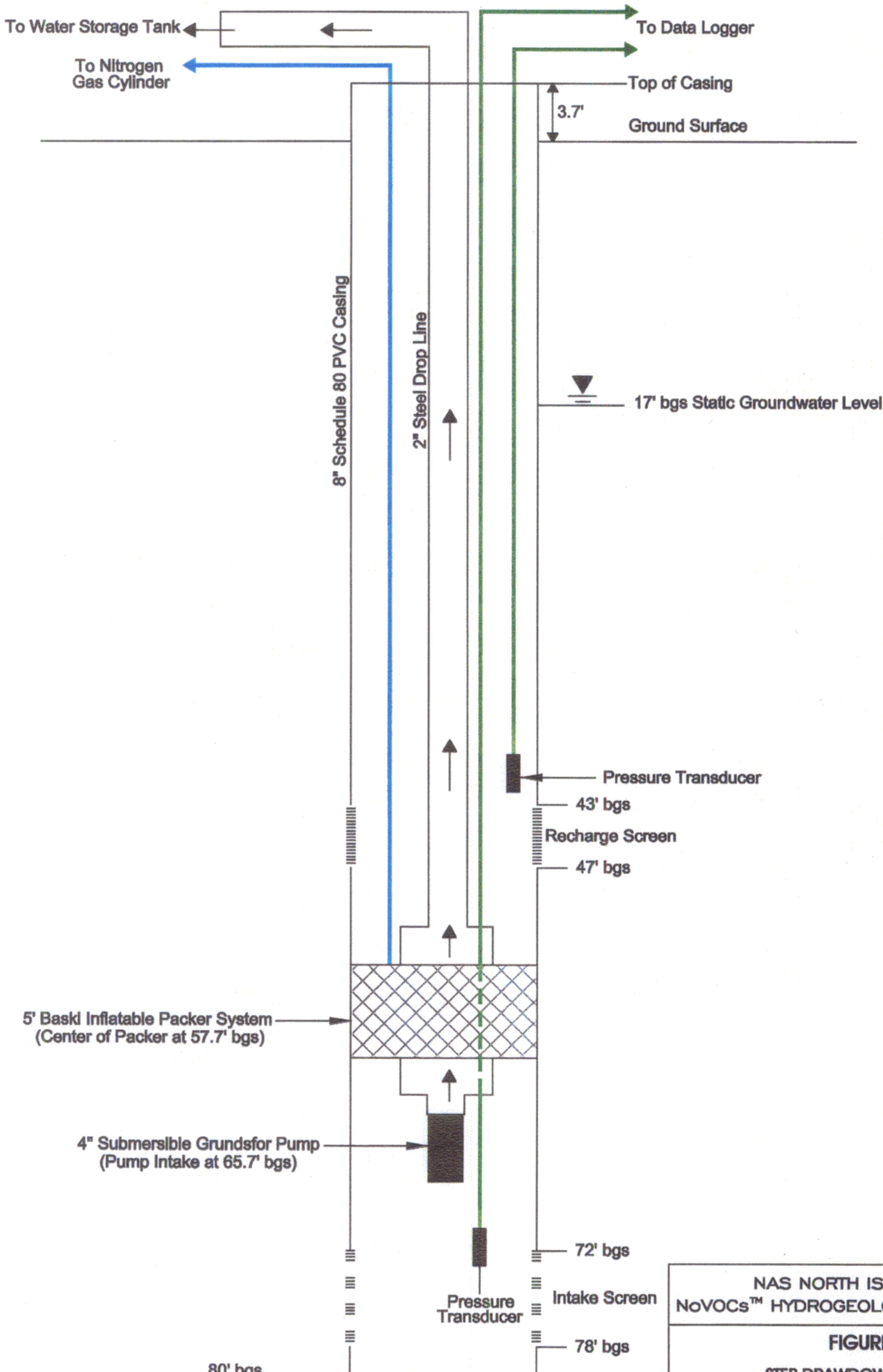


NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-3

INJECTION TEST-UPPER SCREENED INTERVAL
INJECTION WELL CONFIGURATION

Tetra Tech EM Inc.



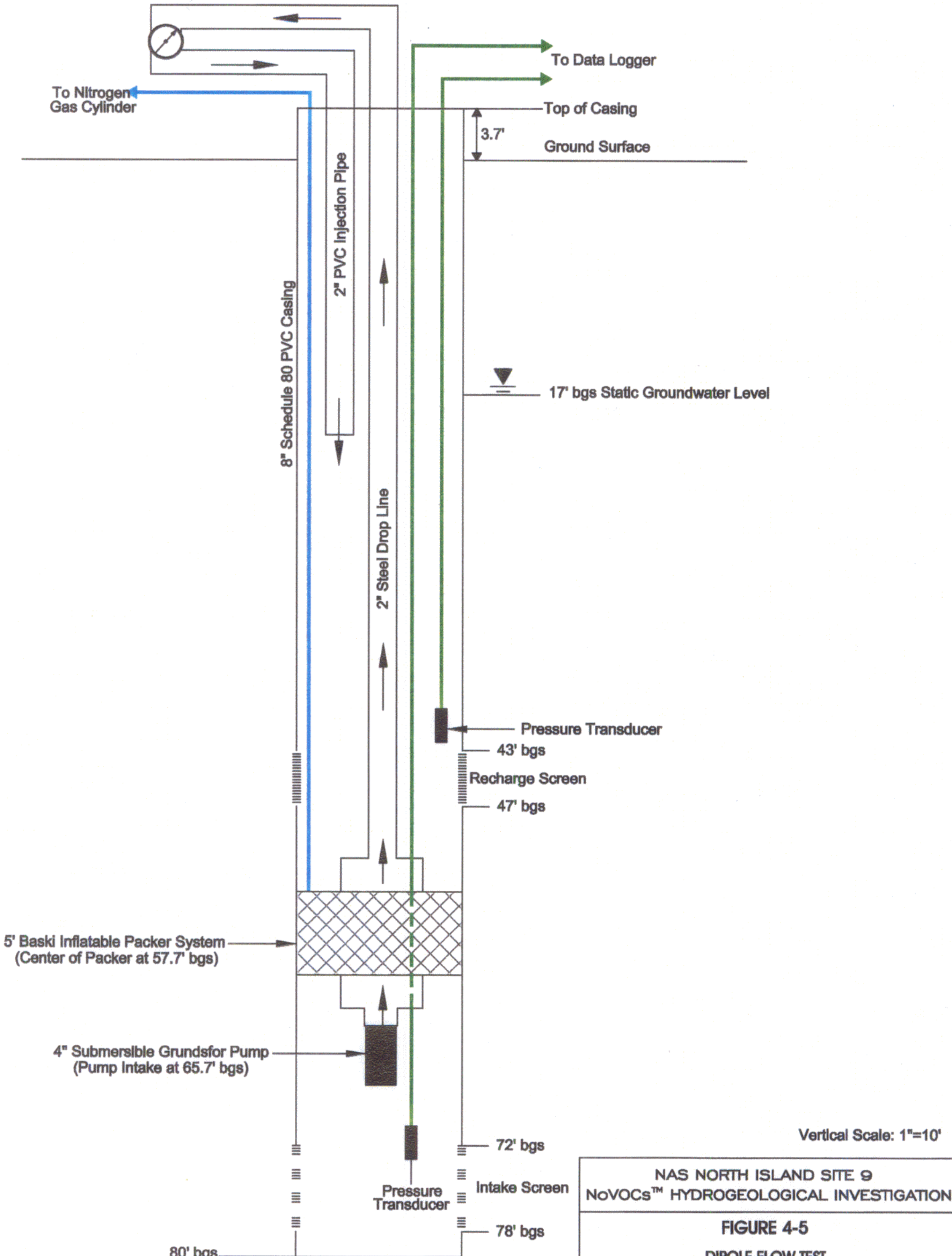
Vertical Scale: 1"=10'

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-4

STEP DRAWDOWN TEST-LOWER SCREENED INTERVAL PUMPING WELL CONFIGURATION

Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-5

DIPOLE FLOW TEST
WELL CONFIGURATION

Tetra Tech EM Inc.

TABLE 4-1

TEST EXECUTION SUMMARY
STEP DRAWDOWN TEST – UPPER SCREEN INTERVAL
JULY 27, 1998
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Pumping Rate	Time	Comments
0	NA	14:22	Static groundwater elevation at 17.35 feet below ground surface in the upper screened portion of the NoVOCs™ well
1	43 gpm	14:30 to 14:47	Water level reached pump intake, a water level decrease of about 37 feet in the upper screened portion of the NoVOCs™ well
Recovery	NA	14:47 to 16:00	Pump shut off; aquifer recovery monitored. Transducer lowered about 5 feet at 15:40.
2	10 gpm	16:00 to 16:11	Water level in well decreased 5.9 feet from initial level in upper screened portion of the NoVOCs™ well
Recovery	NA	16:11 to 16:30	Pump shut off (circuit breaker problem); aquifer recovery monitored.
3	15 gpm	16:30 to 17:15	Water level decreased about 11.0 feet from initial level in the upper screened portion of the NoVOCs™ well
4	20 gpm	17:15 to 18:00	Water level decreased about 14.2 feet from initial level in the upper screened portion of the NoVOCs™ well
Recovery	NA	18:00 to 18:42	Pump shut off; aquifer recovery monitored

Notes:

NA Not applicable
gpm Gallons per minute

TABLE 4-2

TEST EXECUTION SUMMARY
CONSTANT DISCHARGE PUMPING TEST – UPPER SCREEN INTERVAL
JULY 28 THROUGH 30, 1998
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Pumping Rate	Time	Comments
0	NA	07:54 (7/28)	Initial groundwater elevation at 17.79 feet below ground surface in the upper screened portion of the NoVOCs™ well
1	20 gpm	08:00 (7/28) to 16:00 (7/29)	A total drawdown of 16.4 feet observed in the upper screened portion of the NoVOCs™ well
Recovery	NA	16:00 (7/29) to 14:00 (7/30)	Pump shut off; aquifer recovery monitored

Notes:

gpm Gallons per minute
NA Not applicable

TABLE 4-3

TEST EXECUTION SUMMARY
INJECTION TEST – UPPER SCREEN INTERVAL
JULY 31 AND AUGUST 1, 1998
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Injection Rate	Time	Comments
0	NA	14:55 (7/31)	Initial groundwater elevation at 17.47 feet below ground surface.
1	5 gpm	15:00 to 16:00	Water level in well increased 3.3 feet from initial level in upper screened portion of the NoVOCs™ well
2	15 gpm	16:00 to 17:00	Water level increased about 6.0 feet from Step 1 in the upper screened portion of the NoVOCs™ well
3	22 gpm	17:00 to 18:00	Water level increased about 5.1 feet from Step 2 in the upper screened portion of the NoVOCs™ well
4	30 gpm	18:00 to 18:04	Water level increased about 3.6 feet from Step 3 (water discharging at ground surface through piezometer)
5	25 gpm	18:04 to 18:18	Water level increased about 2.5 feet from Step 3 in the upper screened portion of the NoVOCs™ well
Recovery	NA	18:18 (7/31) to 08:15 (8/1)	Aquifer recovery data collected

Notes:

gpm Gallons per minute
NA Not applicable

TABLE 4-4

TEST EXECUTION SUMMARY
STEP DRAWDOWN TEST – LOWER SCREEN INTERVAL
AUGUST 1 AND 2, 1998
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Pumping Rate	Time	Comments
0	NA	12:19 (8/1)	Initial groundwater elevation at 17.19 feet below ground surface in the upper screened portion of the NoVOCs™ well
1a	40 gpm	12:30 to 12:40	Checking integrity of packer seal. Water decreased 11.4 feet from static in lower screened portion of the NoVOCs™ well. Packer seal leaking.
Recovery	NA	12:40 to 13:00	Packer deflated and reinflated
1b	50 gpm	13:00 to 14:00	Recheck packer seal integrity. Packer seal integrity OK. Water level in well decreased 15.1 feet from initial level in lower screened portion of the NoVOCs™ well
2	64 gpm	14:00 to 15:00	Water level decreased about 20.8 feet from initial level in the lower screened portion of the NoVOCs™ well.
Recovery	NA	15:00 to 15:30	Pump shut off; aquifer recovery monitored
3	30 gpm	15:30 to 16:30	Water level decreased about 9.6 feet from initial level in the lower screened portion of the NoVOCs™ well
Recovery	NA	16:30 (8/1) to 0730 (8/4)	Pump shut off; aquifer recovery monitored

Notes:

gpm Gallons per minute
NA Not applicable

TABLE 4-5

TEST EXECUTION SUMMARY
DIPOLE FLOW TEST
AUGUST 5 THROUGH 7, 1998
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Injection Rate	Time	Comments
0	NA	11:29 (8/5)	Initial groundwater elevation at 20.69 feet in upper section of the NoVOCs™ well
1	5 to 6 gpm	11:35 to 12:29	Water level increased about 5.3 feet from initial water level in the upper screened section of the NoVOCs™ well. Water level decreased about 2.2 feet from static water level in lower screened section of the NoVOCs™ well.
2	10 gpm	12:29 to 13:40	Water level increased about 3.3 feet from Step 1 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.5 feet from Step 1 in the lower screened section of the NoVOCs™ well.
3	15 gpm	13:40 to 14:41	Water level increased about 2.8 feet from Step 2 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.0 foot from Step 2 in the lower screened section of the NoVOCs™ well.
4	20 gpm	14:41 to 15:47	Water level increased about 3.8 feet from Step 3 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.8 feet from Step 3 in the lower screened section of the NoVOCs™ well.
5	24 to 25 gpm	15:47 to 16:41	Water level increased about 2.3 feet from Step 4 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.3 feet from Step 4 in the lower screened section of the NoVOCs™ well.
Recovery	NA	16:41 (8/5) to 09:45 (8/7)	Aquifer recovery data collected

Notes:

gpm Gallons per minute
NA Not applicable

TABLE 4-6

WATER QUALITY PARAMETERS
AQUIFER PUMPING TESTS
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND
Page 1 of 2

Date	Time	Temperature (°C)	Specific Conductance (µmhos)	pH	Eh (mv)	Dissolved Oxygen (mg/L)	Salinity (percent)	Turbidity (NTU)
Step Drawdown Test - Upper Screen Interval								
7/22/98	13:25	22	29.7	6.87	32	8.46	2.64	1
7/22/98	13:30	21.8	27.8	7.01	-40	8.48	2.67	53
7/22/98	13:35	22.0	27.3	7.08	-20	8.65	2.68	53
7/22/98	13:40	22.0	27.1	7.12	-29	8.63	2.59	53
7/22/98	--	21.5	27.9	7.17	-89	8.88	2.59	53
7/22/98	15:12	22.2	26.9	7.12	-11	8.72	2.67	1
7/22/98	15:24	21.3	26.9	7.09	-13	8.93	2.68	NM
Average		**21.82**	**27.7**	**7.07**	**-24**	**8.68**	**2.65**	**36**
Constant Rate Pump Test - Upper Screen Interval								
7/27/98	20:20	21.7	23.5	7.03	15	7.76	2.48	67
7/27/98	21:32	21.6	24.4	7.35	42	7.40	2.51	63
7/28/98	08:06	21.5	24.7	7.24	84	7.39	2.47	3
7/28/98	08:17	21.6	24.8	7.21	66	NM	NM	NM
7/28/98	10:23	22.5	24.7	7.33	59	8.44	2.44	60
7/28/98	11:20	22.0	24.5	7.37	30	8.64	2.43	55
7/28/98	12:23	22.0	24.6	7.39	31	8.64	2.43	61
7/28/98	14:26	22.1	23.9	7.39	67	8.54	2.38	54
7/28/98	15:30	21.8	23.6	7.42	18	8.64	2.38	3
7/28/98	16:36	22.5	23.3	7.41	41	9.62	2.34	3
7/28/98	17:33	21.8	23.2	7.43	37	8.54	2.31	50
7/28/98	19:57	21.6	22.8	7.44	31	7.58	2.25	3
7/28/98	21:14	21.5	22.5	7.45	-1	7.46	2.25	0
7/28/98	22:18	21.6	22.3	7.46	-9	7.43	2.22	0
7/28/98	23:09	21.4	22.2	7.47	-14	7.39	2.21	2
7/29/98	00:18	21.6	22.0	7.44	-15	7.33	2.19	0
7/29/98	01:15	21.6	21.7	7.43	-13	7.21	2.19	2
7/29/98	02:17	21.6	23.0	7.43	-7	7.30	2.18	4
7/29/98	03:15	21.6	23.2	7.43	-8	7.56	2.14	3
7/29/98	04:24	21.6	22.8	7.41	-7	7.62	2.13	2
7/29/98	05:19	21.6	23.0	7.44	-16	7.51	2.14	1
7/29/98	06:12	21.6	23.1	7.45	-9	7.56	2.16	5
7/29/98	07:00	21.3	18.7	7.47	-4	7.64	2.15	9
7/29/98	10:25	21.7	23.7	7.48	51	7.92	2.11	1
7/29/98	12:30	22.0	23.1	7.50	49	8.27	2.09	3
7/29/98	14:30	27.4	20.0	7.44	45	8.49	2.09	0
7/29/98	15:54	21.8	22.6	7.49	49	8.38	2.04	2
Average		**21.95**	**23.03**	**7.40**	**22.67**	**7.93**	**2.26**	**17.54**

TABLE 4-6

WATER QUALITY PARAMETERS
AQUIFER PUMPING TESTS
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Date	Time	Temperature (°C)	Specific Conductance (μmhos)	pH	Eh (mv)	Dissolved Oxygen (mg/L)	Salinity (percent)	Turbidity (NTU)
Step Drawdown Test - Lower Screen Interval								
8/1/98	13:34	21.8	24.2	6.97	-14	8.46	2.70	53
8/1/98	14:13	21.7	27.0	7.02	-31	8.37	2.70	2
8/1/98	14:30	21.7	27.0	7.11	-32	8.05	2.71	0
8/1/98	14:52	21.7	27.8	7.06	-32	8.35	2.72	62
8/1/98	15:46	21.9	29.0	7.02	-36	8.33	2.71	3
8/1/98	16:16	21.7	29.4	7.01	-38	8.06	2.72	6
Average		**21.8**	**27.4**	**7.03**	**-31**	**8.27**	**2.71**	**21**

Notes:

°C	Degrees Celsius.
μmhos	Micromhos
mv	Millivolts
mg/L	Milligrams per liter
NTU	Nephelometric turbidity units
NM	Not measured
Eh	Reduction/oxidation potential

5.0 DATA INTERPRETATION

This section interprets and discusses the data collected during the aquifer tests and the tidal influence study, including groundwater tidal influence correction for the pumping test data, calculations of well-specific yield and efficiency, calculations of aquifer hydraulic parameters, calculations of the mean groundwater levels, calculations of fresh water equivalent heads (density correction) and estimation of groundwater flow patterns.

5.1 TIDAL INFLUENCE CORRECTION

Groundwater levels in the vicinity of the NoVOCs™ well are affected by tidal fluctuations in San Diego Bay because of hydraulic communication between the groundwater and the bay and the proximity of the site to the bay. Water level data derived from pumping tests must be corrected for tidal influence before they can be used to estimate aquifer parameters, except when the water level fluctuation caused by tides is insignificant in comparison with drawdown (such as in the pumping well). This section discusses the principles of and approaches to the tidal influence correction, and applies the corrections to the pumping test water level data.

5.1.1 Relationship Between Tide and Groundwater Fluctuation

Observed groundwater level fluctuations can be divided into two components: (1) tidally induced fluctuations, and (2) fluctuations caused by other factors. This relationship can be described by the following equation:

$$\frac{dh'(t)}{dt} = \frac{dh(t)}{dt} - E_{tide} \frac{dH(t - t_{lag})}{dt} \tag{5-1}$$

where

h'	=	Groundwater elevations without tidal influence [L]
h	=	Observed groundwater elevation [L]
H	=	Tidal elevation in surface water body [L]
E_{tide}	=	Tidal efficiency [dimensionless]

t	=	The time when groundwater elevation was measured [T]
t_{lag}	=	Time lag between tidal effects in surface water body and corresponding effects at groundwater observation points [T]

The first term of the right-hand side of Equation 5-1 represents the observed groundwater level fluctuation, and the second term of the right-hand side represents tidally induced groundwater level fluctuation. The left-hand side of the equation represents groundwater fluctuations caused by other factors, such as pumping of groundwater, lateral changes in recharge or discharge in the aquifer, and other daily and seasonal water level changes (such as those caused by barometric pressure changes).

As shown in Equation 5-1, the relationship between the tidal fluctuation in the surface water levels and the tidally induced groundwater level fluctuation is determined by two parameters: tidal efficiency (E_{tide}), and time lag (t_{lag}). The tidal efficiency is defined as the ratio of tidally induced changes in groundwater levels to the tidal changes in the surface water body. The time lag represents the time difference between the tidal changes in the surface water body and corresponding changes in groundwater levels. Both the tidal efficiency and time lag are determined by a number of factors, including aquifer hydraulic conductivity and storativity (or diffusivity), aquifer thickness, and distance from the observation well to the surface water body. The relationship between the tidal influence parameters and the above factors in a homogeneous and isotropic aquifer can be expressed as follows (Jacob 1950; Ferris 1951):

$$E_{tide} = e^{\left(-x\sqrt{\frac{\pi S}{t_p KB}}\right)} \qquad (5\text{-}2)$$

and

$$t_{lag} = x\sqrt{\frac{t_p S}{4\pi KB}} \qquad (5\text{-}3)$$

where

x	=	Distance from the observation well to the coast line [L]
S	=	Aquifer storativity [dimensionless]
K	=	Aquifer hydraulic conductivity [LT^{-1}]
B	=	Aquifer thickness (L)
t_p	=	Tidal period (time between consecutive high and low tides) [T]

Based on Equations 5-2 and 5-3, the tidal efficiency will increase as aquifer hydraulic conductivity and aquifer thickness increase, and decrease as aquifer storativity and the distance from the coast increase. The tidal time lag will decrease as aquifer hydraulic conductivity and aquifer thickness increase, and increase as aquifer storativity and the distance from the coast increase. Based on these relationships, the time lag will generally decrease when tidal efficiency increases. Theoretically, the tidal efficiency and time lag are not functions of time.

Equations 5-2 and 5-3 are based on the following assumptions:

- Tidal fluctuations can be described as a sinusoidal function
- One-dimensional groundwater flow is perpendicular to the shoreline
- The aquifer is homogeneous and isotropic
- The aquifer is under confined conditions
- The shoreline is considered a lateral boundary that is perpendicular to groundwater flow direction
- The observation well fully penetrates the aquifer

In reality, aquifer conditions rarely meet all the above assumptions (Erskine 1991; Serfes 1991). Consequently, tidal efficiency and time lag are generally not calculated from Equations 5-2 and 5-3; the equations have been presented to provide a theoretical definition of tidal efficiency and time lag. Instead, these two parameters are usually determined directly from observed groundwater and surface water level fluctuations. A procedure to calculate tidal efficiency and time lag from the observed groundwater and tidal data is presented in the following section.

5.1.2 Procedure for Calculating Tidal Efficiency and Time Lag

In order to calculate the tidal efficiency and time lag from the observed surface water (San Diego Bay) and groundwater level data, an observation period should be selected during which the groundwater level fluctuations are primarily affected by tide; other factors affecting groundwater levels (such as rainfall infiltration and pumping) should be negligible. From Equation 5-1, if the effects of factors other than tidal fluctuations can be ignored ($dh' / dt = 0$), the observed groundwater fluctuations can be used directly to represent the tidally induced fluctuations, as expressed by the following equation:

$$\frac{dh(t)}{dt} = E_{tide} \frac{dH(t - t_{lag})}{dt} \tag{5-4}$$

For a time period from t_0 to t_1 in the groundwater observation record, the solution of Equation 5-4 can be obtained by integration as follows:

$$\int_{t_0}^{t_1} \frac{dh(t)}{dt} dt = \int_{t_0}^{t_1} E_{tide} \frac{dH(t - t_{lag})}{dt} dt \tag{5-5}$$

This integral can be expressed as follows:

$$h(t_1) - h(t_0) = E_{tide} \left[H(t_1 - t_{lag}) - H(t_0 - t_{lag}) \right] \tag{5-6}$$

Based on Equation 5-6, the tidal efficiency can be calculated as follows:

$$E_{tide} = \frac{h(t_1) - h(t_0)}{H(t_1 - t_{lag}) - H(t_0 - t_{lag})} \tag{5-7}$$

Equation 5-7 represents the tidal efficiency for the period from t_0 to t_1.

In principle, tidal efficiency and time lag are constants that do not vary with time. However, these parameters may vary from time to time because of groundwater flow conditions and inconsistencies in the amplitude and periodicity of tidal fluctuations. In general, various tidal efficiencies can be calculated using Equation 5-7 for different periods of the data. Different time lags can also be determined independently using different data sets. A procedure for calculation of tidal efficiency and time lag is described as follows:

(1) Choose a period in the observed groundwater level record when groundwater fluctuations are almost exclusively caused by the tidal fluctuations.

(2) Identify the high tide and low tide in tidal records, and identify corresponding groundwater high level and low level in groundwater level records.

(3) Calculate tidal time lag as follows:

$$t_{lag} = t_{i(tide)} - t_{i(gw)} \tag{5-8}$$

where

$t_{i(tide)}$	=	Time for the i^{th} high (or low) tide [T]
$t_{i(gw)}$	=	Elevation time for the i^{th} high (or low) groundwater elevation corresponding to the i^{th} high (or low) tide [T]

(4) Calculate the tidal efficiency using the following equation:

$$E_{tide} = \frac{h_i - h_{i-1}}{H_i - H_{i-1}} \tag{5-9}$$

where

H_i	=	The i^{th} high (or low) tidal elevation (L)
h_i	=	The i^{th} high (or low) groundwater elevation corresponding to the i^{th} high (or low) tide [T]

Figure 5-1 presents a graphical illustration of the time lag and tidal efficiency (amplitudes of the tidal fluctuations in San Diego Bay and MW-45) based on a comparison of San Diego Bay water levels and groundwater levels in observation well MW-45.

5.1.3 Calculation of Tidal Efficiency and Time Lag Using April 1998 Tidal Study Data

Tidal efficiency and time lags were calculated based on the groundwater elevation data collected at eight observation wells during the April 1998 tidal influence study. The groundwater elevations in the wells were recorded at 10-minute intervals for 10 days. During this period, the surface water level data in San Diego Bay can be divided into 39 monotonic segments (that is, water levels from high to low or low to high tide). Groundwater levels at all observation wells clearly showed tidally influenced fluctuations that correspond to the tidal fluctuations in San Diego Bay. The average amplitude of tides in the bay for the 10-day period was 5.27 feet, and the average amplitude of groundwater fluctuations in various observation wells ranged from 0.36 to 0.46 feet. The maximum, minimum, and mean tidal amplitude and groundwater fluctuations are presented in Table 5-1.

The tidal efficiency and time lags were calculated for each of the 39 monotonic tidal segments during the 10-day tidal study using the procedure described in section 5.1.2. Table 5-1 shows the maximum, minimum, and mean estimated tidal efficiencies and time lags for the eight observation wells at the site.

As shown in the table, both the tidal efficiency and time lag vary slightly at the various observation well locations, but vary significantly during different tidal cycles, as indicated by the significant difference between minimum and maximum values of tidal efficiency and time lag. The mean tidal efficiency (average tidal efficiency for all 39 tidal periods) at the eight observation wells ranges from 0.07 to 0.09. The higher tidal efficiency values were measured at downgradient observation wells (MW-52 and MW-53), which are the closest to the bay of the wells monitored. The difference between the maximum and minimum tidal efficiency during different tidal cycles was about 0.03 for most of the wells.

The mean time lags (average time lag for all 39 monotonic tidal periods) did not change significantly from well to well, ranging from 69 minutes to 72 minutes. However, the time lags in each well changed considerably during different tidal cycles (Table 5-1).

5.1.4 Procedures for Tidal Correction of Groundwater Drawdown Data

When an aquifer hydraulic test is conducted in a tidally influenced aquifer, groundwater levels are affected by at least two major factors: drawdown from pumping and fluctuation caused by tide. Tidal fluctuation, if significant compared with pumping drawdown, can complicate interpretation of test data. Literature review shows that correction of non-steady state pumping test data for tidal influence has not been much studied and that no readily applicable methods are currently available. Therefore, in this section, two different approaches are developed and discussed. The two approaches—that is, the tidal correction of the drawdown data collected during the upper aquifer zone constant discharge pumping test—are presented in this section.

5.1.4.1 Approach Based on the Linear Relationship Between Groundwater and Tide

As shown in Equation 5-1, observed groundwater level fluctuations in tidally influenced aquifers are the sum of tidally induced fluctuations and water level changes caused by other factors. For the time period from t_0 to t, differential Equation 5-1 can be solved by integration, as follows:

$$\int_{t_0}^{t} \frac{dh'}{dt} dt = \int_{t_0}^{t} \frac{dh}{dt} dt - \int_{t_0}^{t} E_{tide} \frac{dH(t - t_{lag})}{dt} dt \qquad (5\text{-}10)$$

This integral can be expressed as follows:

$$h'(t) = h(t) - h(t_0) - E_{tide}\left[H(t - t_{lag}) - H(t_0 - t_{lag})\right] + h'(t_0) \qquad (5\text{-}11)$$

where

$h'(t)$	=	Tidally corrected groundwater elevation at time t [L]
$h'(t_0)$	=	Tidally corrected groundwater elevation at initial time t_0 [L]
$h(t)$	=	Observed groundwater elevation at time t [L]
$h(t_0)$	=	Observed groundwater elevation at initial time t_0 [L]
$H(t- t_{lag})$	=	Tidal elevation at time $t- t_{lag}$ [L]
$H(t_0- t_{lag})$	=	Tidal elevation at time $t_0- t_{lag}$ [L]
E_{tide}	=	Tidal efficiency [dimensionless]
t_{lag}	=	Time lag [T]

This equation shows that the groundwater elevations corrected for tidal influence can be calculated from the observed groundwater elevations, observed tidal elevations, and tidal influence parameters (tidal efficiency and time lag). The equation also shows that the tidal influence component of changes in groundwater level can be expressed as a linear function of tidal fluctuations in surface water.

Water level drawdowns at time t can be defined as:

$$s(t) = h_{ref} - h(t) \qquad (5\text{-}12)$$

and

$$s'(t) = h_{ref} - h'(t) \qquad (5\text{-}13)$$

where

h_{ref}	=	Reference groundwater level (a constant) [L]
$s(t)$	=	Observed water level drawdown at time t [L]
$s'(t)$	=	Tidally corrected water level drawdown at time t [L]

Using Equations 5-12 and 5-13 to substitute for h(t), $h(t_0)$, h'(t), and $h'(t_0)$ in Equation 5-11, the tidally corrected water level drawdown can be described as follows:

$$s'(t) = s(t) - s(t_0) - E_{tide}\left[H(t_0 - t_{lag}) - H(t - t_{lag})\right] + s'(t_0) \qquad (5\text{-}14)$$

where

$s(t_0)$	=	Observed water level drawdown at initial time t_0 [L]
$s'(t_0)$	=	Tidally corrected water level drawdown at time t_0 [L]

Both Equations 5-11 and 5-14 assume that the tidal efficiency and time lag are constant over the calculation period from t_0 to t. However, as discussed in the previous section, tidal efficiency and time lag are generally not constant for different tidal periods (tidal cycles). In fact, tidal study data collected in April 1998 at the site demonstrate that tidal efficiency and time lag vary significantly over the 10-day period.

Equations 5-11 and 5-14 are the basis of the first approach (linear relationship) used for tidal correction of the groundwater drawdown data. The tide data were obtained from the San Diego Bay station of the National Oceanic and Atmospheric Administration (NOAA). The linear relationship approach for correcting groundwater drawdown data for tidal influence is described as follows:

(1) Identify the high and low points in the bay tide elevation record, and divide the bay tide record into monotonic segments bounded by consecutive high and low tide elevations.

(2) Identify the high and low groundwater levels in the groundwater drawdown data, and divide the groundwater drawdown data into segments that correspond to the monotonic tidal segments identified in step 1.

(3) Compare each of the bay tidal segments with corresponding groundwater drawdown data segments to determine whether the time spans are similar for the two segments. If the time span for a monotonic tidal segment is different from the corresponding drawdown segment, the time scale of the tidal segment is compressed or expanded by linear interpolation to match the drawdown segment.

(4) The first and last groundwater drawdown segments may or may not match a complete monotonic segment of the bay tide, depending on timing of the pumping test in relation to the tide cycles. Therefore, multiple smaller data segments are used to better match the time scale of the early pumping test data.

(5) Shift the time axis of the bay tidal segments based on the range of the time lag values calculated from the April 1998 tidal study data (Table 5-1). Apply the tidal efficiency

(also Table 5-1) to correct each segment of observed groundwater drawdown using the equation:

$$s'(\tau) = s(\tau) - s(0) - E\left[H(0)_0 - H(\tau)\right] + s'(0) \qquad (5\text{-}15)$$

where

$s'(\tau)$	=	Corrected groundwater drawdown for the segment [L]
$s'(0)$	=	Corrected groundwater drawdown at the start of the segment [L]
$s(\tau)$	=	Observed groundwater drawdown for the segment [L]
$s(0)$	=	Observed groundwater drawdown at the start of the segment [L]
$H(\tau)$	=	Tidal elevation for the segment [L]
$H(0)$	=	Tidal elevation at the start of the segment [L]
E	=	Tidal efficiency for the segment [dimensionless]
τ	=	Time since beginning of the segment [T]

(6) The tidal correction procedure is repeated for all segments of the tidal and groundwater drawdown record.

5.1.4.2 Approach Based on the Best-Fit Equation of Groundwater Tidal Fluctuation

In the second approach for tidal correction of groundwater drawdown data, a tidal influence curve (best-fit equation) is generated for the period of the pumping test that reflects only tidal fluctuations. These tidal influence curves are generated for data from each of the observation wells. Using this approach, fluctuations in groundwater levels calculated from the tidal influence curve are subtracted from the observed drawdown data collected during the pumping test. The corrected drawdown can then be used to calculate aquifer parameters.

The tidal influence curves for observation wells within the radius of influence during a pumping test can be derived from the tidal influence curves for data from wells outside the radius of influence or from tidal curves for the bay tide. Tidal data collected at the observation wells before or after the pumping test cannot be used because the bay tide changes significantly with time. During the pumping test, tidal fluctuation at different wells within the pumping aquifer is generally a function of aquifer hydraulic properties and distance from the shoreline but not a function of time, as described in Equations 5-2 and 5-3.

In general, the tidal influence curve at a monitoring well is described as a series of sinusoidal (or cosine) functions as follows:

$$f(t) = A + \sum_{i=1}^{n} B_i \sin[\frac{2\pi}{T_i}(t + \tau_i)] \qquad (5\text{-}16)$$

where

A	=	A constant related to the difference between groundwater and bay tide elevations [L]
B_i	=	The amplitude of the i^{th} tidal constituent [L]
T_i	=	The period of the i^{th} tidal constituent [T]
τ_i	=	The phase of the i^{th} tidal constituent[T]

The amplitude, period, and phase of the tidal function in groundwater are related to the tidal efficiency and time lag of the aquifer and the same parameters of the bay tidal constituents. The bay tidal constituents in turn are caused by the rotation of the Earth about the sun, the moon about the Earth, and the Earth on its axis. The amplitude, period, and phase of each tidal constituents (waves) of the tidal influence function can be calculated through harmonic analysis, which is commonly used to predict ocean tides at various locations in the United States. The phase of the ocean tide is determined by the starting point of the prediction, and the phase of groundwater tidal influence is a function of the starting point of the calculation and time lag behind the ocean tide.

Groundwater level at well MW-20 was observed using a pressure transducer during the entire period of the aquifer test (including step drawdown and constant discharge pumping tests). Well MW-20 is located approximately 800 feet from the NoVOCs™ pumping well and about 140 feet from San Diego Bay. This well is clearly outside the radius of pumping influence. Therefore, the second approach (best-fit equation) was developed using groundwater level data for well MW-20.

The tidal correction procedures for the pumping test drawdown data based on the best-fit equation approach is described as follows:

(1) Plot the groundwater level data collected from well MW-20. Based on Equation 5-16, a best-fit tidal curve (as a sinusoidal equation) can be obtained through harmonic analysis. The plot and best-fit tidal curve are presented in Figure 5-2. The correlation coefficient

(R^2) of the best-fit equation (tidal curve) is 0.96. The tidal curve for MW-20 is described as:

$$f_{MW-20}(t) = 3.60 + 0.21\sin(\frac{2\pi}{25.76}t) + 0.51\sin[\frac{2\pi}{23.78}(t-1.72)] + 0.69\sin[\frac{2\pi}{12.36}(t-6.87)] + 0.29\sin[\frac{2\pi}{11.89}(t-8.92)] \quad (5\text{-}17)$$

(2) Select a time period when the pumping impact is insignificant (from August 1 through 4, 1998, after the deep aquifer zone step drawdown tests), and compare data for well MW-20 with the bay tide and groundwater level data collected from other observation wells (Figures 5-3 through 5-10)

(3) Based on Equation 5-17 and Figure 5-3, generate the tidal influence curve for well MW-45: the elevation constant (A) is calculated

(4) Based on the difference between the average groundwater elevations in wells MW-20 and MW-45; the amplitude constants (B_i) are calculated based on the difference in tidal efficiency between the two wells; the tidal period constants (T_i) are kept the same; and phase constants (τ_i) are adjusted based on the starting time and the different time lags between the two wells. The tidal influence curve for well MW-45 during the period of the constant discharge pumping test is described as follows:

$$f_{MW-45}(t) = 5.00 + 0.057\sin[\frac{2\pi}{25.76}(t+0.79)] + 0.12\sin[\frac{2\pi}{23.78}(t-0.05)] + 0.29\sin[\frac{2\pi}{12.36}(t-7.94)] + 0.15\sin[\frac{2\pi}{11.89}(t-8.11)] \quad (5\text{-}18)$$

(5) Repeat Steps 3 and 4 to obtain the tidal influence curves for data from wells MW-46, MW-47, MW-48, MW-49, MW-52, MW-53, and MW-54. Equation 5-17 and Figures 5-3 through 5-10 are used for determining the tidal influence functions. The tidal influence curves for these wells during the constant discharge pumping test are described by the following equations:

$$f_{MW-46}(t) = 4.77 + 0.05\sin[\frac{2\pi}{25.76}(t+0.31)] + 0.14\sin[\frac{2\pi}{23.78}(t-1.42)] + 0.26\sin[\frac{2\pi}{12.36}(t-8.13)] + 0.16\sin[\frac{2\pi}{11.89}(t-8.32)] \quad (5\text{-}19)$$

$$f_{MW-47}(t) = 4.51 + 0.06\sin[\frac{2\pi}{25.76}(t + 2.95] + 0.142\sin[\frac{2\pi}{23.78}(t + 0.63)] + 0.283\sin[\frac{2\pi}{12.36}(t - 7.78)] + 0.163\sin[\frac{2\pi}{11.89}(t - 7.66)] \quad (5\text{-}20)$$

$$f_{MW-48}(t) = 4.71 + 0.12\sin[\frac{2\pi}{25.76}(t + 1.63)] + 0.163\sin[\frac{2\pi}{23.78}(t + 0.55)] + 0.26\sin[\frac{2\pi}{12.36}(t - 8.60)] + 0.19\sin[\frac{2\pi}{11.89}(t - 9.15)] \quad (5\text{-}21)$$

$$f_{MW-49}(t) = 4.51 + 0.02\sin[\frac{2\pi}{25.76}(t + 0.30)] + 0.06\sin[\frac{2\pi}{23.78}(t - 0.78)] + 0.266\sin[\frac{2\pi}{12.36}(t - 8.09)] + 0.167\sin[\frac{2\pi}{11.89}(t - 8.38)] \quad (5\text{-}22)$$

$$f_{MW-52}(t) = 4.76 + 0.02\sin[\frac{2\pi}{25.76}(t + 1.86)] + 0.08\sin[\frac{2\pi}{23.78}(t - 0.31)] + 0.205\sin[\frac{2\pi}{12.36}(t - 7.91)] + 0.08\sin[\frac{2\pi}{11.89}(t - 9.14)] \quad (5\text{-}23)$$

$$f_{MW-53}(t) = 4.49 + 0.02\sin[\frac{2\pi}{25.76}(t + 1.86)] + 0.14\sin[\frac{2\pi}{23.78}(t - 1.42)] + 0.26\sin[\frac{2\pi}{12.36}(t - 8.13)] + 0.16\sin[\frac{2\pi}{11.89}(t - 8.32)] \quad (5\text{-}24)$$

$$f_{MW-54}(t) = 5.04 + 0.035\sin[\frac{2\pi}{25.76}(t + 0.31)] + 0.103\sin[\frac{2\pi}{23.78}(t - 1.08)] + 0.275\sin[\frac{2\pi}{12.36}(t - 8.13)] + 0.16\sin[\frac{2\pi}{11.89}(t - 8.32)] \quad (5\text{-}25)$$

(6) Calculate tidal fluctuation in groundwater using the above tidal influence equations for data from all observation wells. Subtract the tidal fluctuation from the observed groundwater elevations, and calculate tidally corrected drawdown from the tidally corrected groundwater elevations. Using data for well MW-45 as example, the corrected drawdown is calculated using the following equation:

$$s^*(t) = [h(0) - f_{MW-45}(0)] - [h(t) - f_{MW-45}(t)] \quad (5\text{-}26)$$

where

s*(t)	=	Tidally corrected groundwater drawdown [L]
h (0)	=	Observed groundwater elevation at the beginning of the pumping test [L]
h (t)	=	Observed groundwater elevation during the pumping test [L]
f_{MW-45} (0)	=	Calculated groundwater elevation from the tidal influence curve at the beginning of the pumping test [L]
f_{MW-45} (0)	=	Calculated groundwater elevation from the tidal influence curve at the beginning of the pumping test [L]

5.1.5 Tidal Influence Correction for the Constant Pumping Test

As shown in Figures D2 through D6 in Appendix D, groundwater level data collected during the constant discharge pumping test in the upper aquifer zone showed significant tidal influence. In order to use the pumping test data to calculate aquifer hydraulic parameters, the observed groundwater drawdown must be corrected for tidal influence. The goal of the tidal influence correction is to separate groundwater drawdown caused by pumping from groundwater fluctuations caused by tidal influence, only the pumping-induced groundwater drawdown is used to calculate aquifer parameters.

Two tidal influence correction approaches are developed and discussed in Section 5.1.4. Both approaches are used to correct the drawdown data collected during the constant discharge pumping test in the upper aquifer zone. The two key tidal influence parameters, tidal efficiency and time lag, are applied in the first approach to derive fluctuations in groundwater caused by tides at the observation wells. The parameter values are initially calculated from the April 1998 tidal study data. Because the bay tide during the pumping test (July/August 1998) was different from the tide in April 1998, the parameters are adjusted to provide the best results of tidal influence correction. Table 5-2 shows the adjusted tidal efficiency and time lags used for the tidal influence correction.

Observed San Diego Bay tide and groundwater levels in well MW-20, the simulated tidal influence (curves), and observed groundwater levels for well MW-45 during the constant discharge pumping test are compared in Figure 5-11. The figure shows that the tidal influence decreased with distance from the bay, and that the simulated tidal influences using the two different approaches are similar.

Figures 5-12 through 5-19 compare the observed and corrected groundwater drawdown data at different observation wells for the constant discharge pumping test. As shown in these figures, the original observed groundwater drawdown graphs indicate significant tidal influence. After correction for tidal influence, the groundwater drawdown curves show typical groundwater level drawdown caused by pumping. The figures also show that the tidal influence corrections using the two different approaches are generally in close agreement. The corrected groundwater drawdown data using the linear relationship approach are applied in Section 5.3 to calculate aquifer parameters.

In summary, two new approaches for tidal correction of groundwater drawdown data collected during a pumping test have been developed. The corrected drawdown data using both approaches correlated reasonably well with each other and reflect typical pumping test responses. Some uncertainties associated with both tidal correction approaches include impact of aquifer heterogeneity, differences in tidal fluctuation during different tidal periods (tidal cycles), and interpolation of tidal data to match frequent data records at the early stage of the pumping test.

5.2 CALCULATION OF SPECIFIC CAPACITY AND WELL EFFICIENCY

This section presents the calculations of specific capacity and well efficiency for the NoVOCs™ well. The calculations are based on water level data collected from the step-drawdown test conducted in the upper screened portion of the well (screened in the upper aquifer zone), the step-drawdown conducted in the lower screened portion (screened in the deep aquifer zone), and the water injection test conducted in the upper screened portion.

5.2.1 Specific Capacity Calculation

Specific capacity of a pumping well is calculated based on (1) the pumping rate and measured maximum drawdown for pumping tests, or (2) the injection rate and maximum water level rise for injection tests (assuming the drawdown and water level rise had stabilized) during each test step. The upper aquifer zone step-drawdown test was conducted in three steps. The upper aquifer zone step-injection test and the deep aquifer zone step-drawdown pumping test were each conducted in four steps. The specific capacity is calculated using the following equation:

$$q_i = \frac{Q_i}{s_i} \tag{5-27}$$

where

q_i	=	Specific capacity $[L^2T^{-1}]$
Q_i	=	Pumping (or injection) rate $[L^3T^{-1}]$
s_i	=	Maximum drawdown (or water level rise) [L]

Figures C1, E1, and F1 (Appendices C, E, and F) show the water levels during the step tests. Table 5-3 shows the step test data and calculated specific capacities for each step of the tests. Based on the upper aquifer step-drawdown test, specific capacity of the NoVOCs™ well calculated for various steps ranges from 1.35 to 1.70 gpm/ft, with the average of 1.48 gpm/ft. The upper aquifer injection test shows similar results, and the calculated specific capacity ranges from 1.45 to 1.57 gpm/ft, with the average of 1.50 gpm/ft. The specific capacity values estimated from the deep aquifer step-drawdown test are higher than for the upper aquifer zone. The calculated specific capacity for the deep aquifer ranges from 3.02 to 3.51 gpm/ft, and the average specific capacity is 3.22 gpm.

5.2.2 Well Loss and Well Efficiency

The theory and concept of well loss and well efficiency and applied approaches for step-drawdown test data analysis have been extensively discussed in the literature. Currently, there are still different theories and approaches to calculate well efficiency. This section presents a brief evaluation of different approaches (Section 5.2.2.1) and calculation of well loss and well efficiency for the NoVOCs™ well based on the step-drawdown and step-injection test data (Section 5.2.2.2).

5.2.2.1 Evaluation of Different Approaches

The discussion of well loss and well efficiency are somewhat conflicting and confusing, as reflected in the literature (Jacob 1947; Rorabaugh 1953; Driscoll 1986; and Kawecki 1995). According to Jacob (1947), total drawdown in a pumping well can be divided into two components: (1) aquifer drawdown that can be described as a linear (first order) function of pumping rate and (2) well loss (caused by turbulent flow) that can be described as an second-order function of the pumping rate, as follows:

$$s = BQ + CQ^2 \tag{5-28}$$

where

s	=	Total drawdown (or water level rise) in the pumping (injection) well [L]
Q	=	Pumping rate $[L^3T^{-1}]$
B	=	Aquifer drawdown coefficient $[L^{-2}T]$
C	=	Well loss coefficient $[L^{-5}T^2]$

Rorabaugh (1953) proposed a more general empirical form of well loss that is described as a n^{th}-order function of the pumping (or injection) rate. Thus, the total drawdown can be expressed as follows:

$$s = BQ + CQ^n \tag{5-29}$$

Step-drawdown tests are commonly used to determine B, C, and n. Rorabaugh (1953) used n values ranging from 2.43 to 2.82; however, Lennox (1966) reported that n=3.5 was more suitable for his step-drawdown test data analysis. In practice, Equation 5-28 has been more widely used and the well loss component is generally considered a second-order function of the pumping rate (n=2). BQ represents aquifer drawdown caused by pumping, and CQ^2 represents the well loss. Once the coefficients B and C are determined, the well efficiency E_{well} (in percent) is calculated as follows:

$$E_{well} = \frac{s - CQ^2}{s} \times 100 \tag{5-30}$$

Driscoll (1986) pointed out that Jacob's and Rorabaugh's definitions of well loss and well efficiency were inadequate and that their assumptions that well loss is attributable to turbulent flow and aquifer drawdown is attributable to laminar flow were incorrect. Based on Driscoll (1986), a portion of the CQ^2 term might actually come from aquifer drawdown and portion of BQ term might include well losses. Driscoll's conclusion was reportedly based on testing of hundreds of wells, however, no details were given regarding the tests and data.

Kawecki (1995) concluded that traditional methods of analyzing step-drawdown test data produce information (well loss and well efficiency) that can be misleading, inaccurate, or meaningless. Kawecki's conclusion is based on the assumption that well losses include both linear and nonlinear components.

Kawecki separated the aquifer drawdown coefficient (B) into B_1 and B_2; where B_1 represents the "true aquifer drawdown" coefficient as a function of "real well radius" and time, and B_2 represents the linear well loss coefficient.

Calculating the well efficiency based on the "true aquifer drawdown" and "real well radius" is not a simple task because the "true aquifer drawdown" cannot be readily measured in most cases. Calculated aquifer drawdown is generally not accurate because of uncertainties associated with the parameters and model assumptions. The methods provided by Driscoll (1986, page 558) and Kawecki (1995) both require accurate values for aquifer and pumping well parameters. Driscoll's and Kawecki's examples show that the calculated well efficiencies based on the aquifer and pumping well parameters can have a large range of values because of uncertainties of the estimated parameter values. Therefore, the methods by Driscoll and Kawecki are inaccurate and impractical.

Dawson and Istok (1991) proposed two methods to determine the well efficiency. The first method is similar to the Driscoll (1986) method that requires calculation of the theoretical aquifer drawdown based known aquifer transmissivity and storativity values. The second method plots distance-drawdown data from at least three observation wells and extrapolates a straight fitted line to project aquifer drawdown at the pumping well. There are two problems with this method: (1) aquifer drawdown is not a linear function of distance, nor a logarithmic linear function of distance because Jacob simplification of Theis equation is not valid for short duration of step-drawdown tests; and (2) a large extrapolation will pose significant error in determining the actual aquifer drawdown at the pumping well. Both methods proposed by Dawson and Istok, therefore, are also inaccurate and impractical.

Well efficiency calculation in this study is based on the traditional concepts that well losses are caused by turbulent flow near and within the pumping well and aquifer drawdown is a result of laminar flow. The well losses can be described as a second-order function of pumping rate and aquifer drawdown is determined as a linear function of the pumping rate (Equation 5-28). For this study, it is believed that Equations 5-28 and 5-30 is adequate and applicable to calculate the well efficiency.

5.2.2.2 Calculation

Well loss and well efficiency can be calculated using graphical methods and computational approaches based on step-drawdown pumping test data. A simple graphical method that has been widely used is to plot s/Q versus Q (Bierschenk 1964). Rearranging Equation 5-28, s/Q can be expressed as:

$$\frac{s}{Q} = B + CQ \tag{5-31}$$

Based on Equation 5-31, s/Q versus Q plots should yield a straight line with slope C and y-axis intercept B.

The disadvantages of this graphical approach are: (1) high uncertainty because multiple steps (at least three) of step-drawdown test data may not adequately fit a straight line (low correlation coefficient); and (2) calculation error will increase significantly when the pumping rate is relatively low and well loss is small (nearly a horizontal line).

The straight line graphical method is not appropriate for analyzing the NoVOCs™ well step test data because s/Q versus Q plots are scattered. The data poorly match a straight line (correlation coefficient, R^2, is less than 0.62; see Figures 5-20 and 5-21). In some cases, a straight line cannot be obtained. Examples of s/Q versus Q are presented in Figures 5-20 and 5-21.

A new graphical approach developed for this investigation was therefore used instead to calculate aquifer drawdown and well loss coefficients (B and C) in this study. The observed total drawdown (s) versus pumping rate (Q) is plotted and a best-fit second order polynomial function is generated using the least-square method (Figure 5-22 through Figure 5-24). Based on Equation 5-29, parameters B and C are determined by the best-fit curves. Figures 5-22 through 5-24 show that the correlation coefficients (R^2) of the best-fit equations range between 0.97 to 0.99. For the upper aquifer injection test, water level rise is used instead of drawdown (Figure 5-23).

Well efficiency calculation results are presented in Table 5-4. As shown in the table, the calculated well efficiencies for both shallow and deep NoVOCs™ wells are quite high, ranging from 77 to 99 percent. These efficiencies indicate that well losses through the well screen and sand pack are relatively low for

the pumping and injection rates used in the step tests. The well efficiency will decrease when pumping rates increase.

Table 5-4 also shows that the shallow well injection efficiency (average 97 percent) is higher than the pumping efficiency (average 82 percent). There are several explanations for the higher injection efficiency. First, the shallow well was redeveloped just before the injection test because of the inadvertent injection of turbid water from a dirty hose. The well was subsequently pumped intensively (five times the volume of water injected) to clean the well. Second, the injected water was clean tap water that was less turbid than the aquifer water being pumped. Third, uneven cuts of screen slots between the inside and the outside of the well screen may cause outward (injection) flow to be less turbulent than inward (pumping) flow.

The injection efficiency calculated using the step-injection test data is consistent with the well efficiency based on measured water level rises inside and outside of the well screen (upper piezometer data). Well efficiency was also evaluated using the dipole test data (see Section 5.5 of this report). The dipole test data may be more representative of the NoVOCs™ operation efficiency because injected water was drawn directly from the deep aquifer. Conversely, the injected water used for the upper aquifer injection test was clean tap water. Clean tap water has different physical and chemical characteristics (particularly turbidity, pH, and Eh) from the aquifer water, and it may have affected the injection test results.

5.3 AQUIFER HYDRAULIC PARAMETER CALCULATION

This section analyzes the data from the constant discharge pumping test conducted in the upper screened portion of the NoVOCs™ well and presents calculations of values for various aquifer hydraulic parameters. Many analytical models are available to analyze pumping test data and calculate aquifer hydraulic parameters. Different models were developed to simulate a variety of aquifer conditions. The first and most critical step in a pumping test data analysis is to select an appropriate model (or models) for the specific aquifer conditions, pumping and observation well construction, and pumping test configurations.

The analytical model for the NoVOCs™ well pumping test data evaluation was selected based on the site hydrogeologic conceptual model, the pumping test configuration (including pumping and observation well construction), and the pumping test drawdown response characteristics. Section 5.3.1 summarizes the site hydrogeology and presents the site hydrogeologic conceptual model. Section 5.3.2 describes the

pumping test configuration. Section 5.3.3 discusses the drawdown response characteristics of the pumping test. Section 5.3.4 discusses selection of the analytical model, and describes the selected model and its applicability. The results of parameter calculation are discussed in Section 5.3.5.

5.3.1 Site Hydrogeologic Conceptual Model

The site hydrogeology has been discussed in Section 2.5. The site hydrogeological conceptual model for the tested aquifer is summarized as follows:

- The aquifer is a thick layer of fine sand that is generally composed of artificial fill and shallow marine-deposited sediments. The aquifer extends from the ground surface to a depth of approximately 105 feet bgs across the site.

- The aquifer is underlain by an impermeable layer (aquitard) of clay (the B clay), which forms the base of the aquifer. Several less permeable layers such as dense or silty sand and the A silt/clay exist within the aquifer in variable thicknesses (generally less than a few feet); none of these less permeable layers behave as significant aquitards because they are relatively thin and lack lateral continuity.

- Although the aquifer is heterogeneous and anisotropic in a large scale, it can be considered homogenous and horizontally isotropic within the zone of pumping influence because the grain size of the fine sand layer is relatively uniform. The aquifer is vertically anisotropic.

- The aquifer is generally under unconfined conditions. The lower portion of the aquifer below the dense sand layer may be under semiconfined conditions.

- The initial water level in the tested aquifer was observed at approximately 17 feet bgs. Groundwater generally flows to the west toward San Diego Bay; however, the groundwater gradient is small and relatively flat.

- Groundwater recharge and discharge are primarily through lateral flow. Vertical infiltration is another source of groundwater recharge. No precipitation occurred during the pumping test period; therefore, the vertical recharge is negligible.

- San Diego Bay is considered a lateral boundary of the aquifer. However, the drawdown responses from the pumping test do not reach the bay, which is approximately 1,000 feet from the test site. Consequently, boundary effects of pumping are considered insignificant.

- The aquifer is tidally influenced. Tidal influence correction may be needed for the drawdown responses in the observation wells.

5.3.2 Constant Discharge Pumping Test Configuration

Pumping test configuration is important in selecting analytical models. Construction details of the pumping and observation wells, the pumping rate and duration, and the spatial orientation of the observation wells for this pumping test study are discussed in Sections 4.1 and 4.3. The constant discharge pumping test configuration was as follows:

- Groundwater was pumped from the upper screened interval of the NoVOCs™ well, which is 43 to 47 feet bgs.
- Pumping well diameter is 8 inches, and boring diameter is 14 inches (including sand pack).
- Pumping rate was kept constant at 20 gpm.
- Pumping duration was 32 hours.
- Initial groundwater level was approximately at 17 feet bgs.
- Saturated thickness of the tested aquifer was estimated at 88 feet.
- Drawdown was monitored in 10 observation wells surrounding the pumping well, but the data logger malfunctioned at two of the observation wells (MW-50 and -51).
- Distances between the observation wells and the pumping well range from 27.7 to 107.9 feet.
- Most of the observation wells have 5-foot screens, except for MW-54 which has a 40-feet screened interval.
- The observation wells are screened at various depths of the aquifer, ranging from 38 to 78 below ground surface.
- The pumping well and all of the observation wells are all partially penetrating wells.

Table 5-5 summarizes the pumping test configuration; this information was used for data interpretation and calculation of aquifer hydraulic parameters.

5.3.3 Drawdown Response Characteristics

In general, drawdown data from the pumping and observation wells are plotted in linear, semilogarithmic, and logarithmic scales. By comparing the drawdown plots with type curves, many important features of the aquifer conditions can be characterized. Some of the important features include well loss or wellbore

storage effects, pumping rate variations, leaky aquifer condition, positive (recharge) or negative (impermeable) boundaries, and delayed yield effects.

Evaluation of drawdown responses for this pumping test study is complicated because of tidal influences during the test. The magnitude of the maximum observed drawdowns in each of the observation wells is similar to the magnitude of the tidal fluctuations in the aquifer (see Figures 5-12 through 5-19). Therefore, data cannot be analyzed before tidal correction is made. The tidal influence correction procedure and corrected drawdown results were described in Section 5.1 of this report. The drawdown data analysis of all the observation wells is based on the corrected data. The pumping well drawdown (more than 16 feet) was significantly greater than the tidal fluctuations in the groundwater level (less than 0.8 feet). Consequently, the pumping well data do not need correction for tidal influence.

Table 5-6 summarizes the drawdown responses for all wells during the constant discharge pumping test. The initial response time is the time at which drawdown in an observation well is first positively identified. The water levels were affected by tidal influence, and the maximum drawdown values presented in Table 5-6 may include numerical error caused by the tidal correction.

The initial response time and maximum drawdown observation wells show that the wells constructed at different depths all responded to pumping in the upper aquifer zone. There are slight variations in response time and maximum drawdown at the well cluster nearest to the pumping well (MW-45, MW-46, and MW-47). These slight variations disappeared with distance from the pumping well, as noted in well cluster MW-48 and MW-49, with the response time increasing and maximum drawdown decreasing with depth. This type of response shows that the vertical hydraulic connection between the upper aquifer zone and lower aquifer zone is good; the dense or silty sand layers do not behave as a significant aquitard.

Table 5-6 also shows that the maximum drawdown and response time in the observation wells vary inversely with distance from the pumping well. This inverse relationship indicates that the aquifer is relatively homogeneous and isotropic in horizontal directions.

The log-log plots of the drawdown data for the observation wells (Figures 5-25 through 5-32) shows that the early data follow the Neuman type curve A closely. These early data were recorded in a short period during which the tidal influence is insignificant; therefore, tidal correction is minimal. The corrected late drawdown data clearly show the delayed yield effects that may be attributed to delayed gravity water

releases near the water table or the vertical flow component caused by partially penetrating pumping and observation wells. The late data may also include errors in the tidal influence correction.

The following summarizes the drawdown responses of the observation wells during the constant discharge pumping test:

- Drawdown responses were identified in all of the observation wells within a radius of 108 feet; positive identification of drawdown is defined as drawdown is greater than 0.01 feet (any data recorded below 0.01 feet include significant transducer and data logger error).

- Early drawdown responses in the wells show that the data plots closely follow the Theis-type curve; the intermediate and later data indicate delayed gravity yield effects.

- In horizontal directions, maximum drawdown decreases, while the response time increases, with distance from the pumping well, suggesting horizontal homogeneity and isotropy of the aquifer.

- In vertical directions, slight differences in maximum drawdown and responding time were observed among the well clusters 30 feet away from the pumping wells. The differences are less distinguishable in the well cluster 60 feet from the pumping well. These differences may indicate that vertical anisotropy exists within the tested aquifer; however, a significant or continuous aquitard probably does not exist between the upper and lower aquifer zones.

5.3.4 Selection of Analytical Model

Based on the site hydrogeologic conceptual model, the pumping test configuration, and drawdown response analysis discussed in the previous sections, the tested aquifer is considered a thick unconfined aquifer with some vertical anisotropy. Both the pumping well and observation wells partially penetrate the aquifer. Neuman's delayed yield model for partially penetrating wells in an unconfined aquifer (Neuman 1975) was selected as the most appropriate analytical model for the pumping data test analysis.

Neuman's model simulates two stages of groundwater release from an unconfined aquifer to a pumping well. At the early stage of the test, groundwater is released from the aquifer by water pressure decreases and aquifer compression. At the later stage, groundwater is primarily released by gravity drainage of the aquifer matrix (delayed yield), which usually causes a decrease in the groundwater drawdown rate.

Four parameters can be calculated by curve matching techniques used in the Neuman method: transmissivity (T), storativity (S), specific yield (S_y), and Neuman delayed yield factor (β). Aquifer transmissivity is defined as hydraulic conductivity multiplied by aquifer thickness; it measures the volume of groundwater that flows through a vertical area defined by unit width and entire thickness of the aquifer per unit time under unit groundwater gradient. Storativity measures the aquifer potential for water release by pressure decrease and aquifer compression, defined as the volume of water released from storage per unit surface area of aquifer per unit decline in hydraulic head. Specific yield measures unconfined aquifer potential for water release by gravity drainage; it is defined as the volume of water released from storage in an unconfined aquifer per unit aquifer volume. The Neuman delayed yield factor measures the effect of delayed yield from vertical gravity drainage and is related to the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity (K_Z/K_r), defined as follows (Neuman 1975):

$$\frac{K_Z}{K_r} = \beta \frac{b^2}{r^2} \qquad (5\text{-}32)$$

where

β	=	Neuman delayed yield factor [dimensionless]
b	=	Saturated thickness of the aquifer [L]
r	=	Distance from the pumping well to the observation well [L]
K_Z	=	Vertical hydraulic conductivity of the aquifer [LT^{-1}]
K_r	=	Horizontal hydraulic conductivity of the aquifer [LT^{-1}]

5.3.5 Results and Discussion

Aquifer hydraulic parameters were calculated using the groundwater pumping test data analysis software package AQTESOLV™ (Duffield and Rumbaugh 1991; HydroSOLVE 1996). The Neuman delayed yield model for partially penetrating wells in unconfined aquifers was selected to analyze the groundwater drawdown data corrected for tidal influence. Log-log plots of drawdown versus time were prepared, and the plots were matched visually with the Neuman type curves. The automatic matching option (using the least-square computational approach) offered by AQTESOLV™ was not used because the computational method is insensitive to the early data match and biased toward the data in the late stage of the test. The late data may include more errors caused by tidal influence and tidal correction. In addition, early data matched to Neuman's type curve A is important for accurate estimation of aquifer hydraulic parameters.

Figures 5-25 through 5-32 show the drawdown plots and the Neuman type curve matching for the various observation wells. As shown in the figures, the Neuman delayed yield type curves match well with the corrected drawdown plots. The drawdown data clearly illustrate the delayed gravity drainage effects. The curve matches in these figures indicate that the aquifer parameter calculation based on the pumping test data is representative.

Table 5-7 presents the results of the aquifer hydraulic parameter calculation using AQTESOLV™. The calculated aquifer hydraulic parameters are summarized as follows:

- The calculated aquifer transmissivity ranges from approximately 2,200 to 2,780 ft^2/day. The aquifer hydraulic conductivity was calculated based on the saturated aquifer thickness of 88 feet, ranging from 25 to 32 feet per day (ft/day) or 0.009 to 0.011 cm/sec. The range of the estimated hydraulic conductivity is typical for fine sand, which is consistent with the aquifer's lithologic conditions at the site.

- The estimated aquifer storativity ranges from approximately 0.001 to 0.008. In the Neuman delayed yield model, storativity represents the elastic release of water from the aquifer matrix at an early stage of the pumping test.

- Specific yield of the testing aquifer ranges from 0.02 to 0.12, approximately one to two orders of magnitude greater than the storativity values. The estimated specific yield values are within the typical range for unconfined aquifers.

- The estimated ratio of vertical to horizontal hydraulic conductivity ranges from 0.08 to 0.3. The ratios were calculated from the Newman delayed yield factor based on equation 5-32. The calculated ratios indicate the aquifer is considerably anisotropic in the vertical direction.

Generally, the estimated aquifer hydraulic conductivity values may represent the average horizontal properties of the testing aquifer. The hydraulic conductivity values calculated from data for the observation wells near the pumping well may be more representative of the upper zone condition. The calculated transmissivity, storativity and specific yield values are relatively constant for various depths of screened intervals and different distances from the pumping well, showing that the hydraulic property of the aquifer is relatively homogeneous.

5.4 DETERMINATION OF GROUNDWATER FLOW PATTERNS

Previous site investigations indicate that groundwater generally flows west in the vicinity of the NoVOCs™ well. However, the mean groundwater flow direction and the horizontal and vertical

hydraulic gradients have not been adequately characterized in those investigations because tidal effects and variable groundwater densities caused by sea water intrusion were not considered. This section discusses the principles, procedures, and results of groundwater flow pattern determination, including mean groundwater level calculation from tidally influenced water levels and density correction for groundwater hydraulic gradient.

5.4.1 Mean Groundwater Level Calculation from Tidally Influence Water Levels

One widely applied method to calculate mean groundwater elevation from tidally influenced water levels was developed by Serfes (1991). The Serfes method is a three-step filtering approach (calculating moving averages) that uses hourly groundwater level data collected during a 70-hour period. The three-step filtering approach provides more accurate average groundwater levels than the straight arithmetic mean. The Serfes method was modified as explained below because water level data unaffected by aquifer testing for 70-hour periods were not available. The periods of data unaffected by pumping tests ranged from 30 to 62 hours. Also, the Serfes method was modified to allow the use of data collected more frequently than the 1-hour interval specified by Serfes (1991). Water levels were monitored at 20-minute intervals for the upper aquifer zone wells and at 15-second intervals for some of the lower aquifer zone wells.

The modified method is based on an average period of approximately 25 hours for a complete tidal cycle consisting of two high tides and two low tides. The procedures for the modified method for data of 20-minute frequency are as follows:

1. For a 50- to 75-hour groundwater elevation data series $\{H_i,\ i = 1, 2, \ldots, n\}$ with $149 \le n \le 224$, compute the first sequence of means $\{X_j, j = 1, 2, \ldots, n-74\}$ as follows:

$$X_j = \frac{1}{75}\sum_{m=0}^{74} H_{m+j} \quad where\ j = 1,2,\ldots,n-74 \qquad (5\text{-}33)$$

   where

   X_j = The first sequence of means [L]

   H_{m+j} = Groundwater elevation data in 20-minute interval [L]

2. Then, the second sequence of means $\{Y_k\}$ $\{k=1,2, \ldots, n-142\}$ is calculated as follows:

$$Y_k = \frac{1}{75}\sum_{m=0}^{74} X_{m+k} \quad where \;\; k = 1,2,\ldots,n-148 \tag{5-34}$$

where

Y_k	=	The second sequence of means [L]
X_{m+k}	=	The first sequence of means [L]

3. Finally, the mean groundwater elevation M is calculated as follows:

$$M = \frac{1}{n-148}\sum_{k=1}^{n-148} Y_k \tag{5-35}$$

where

M	=	The mean groundwater elevation [L]

The mean groundwater elevations for wells MW-45, MW-47, and the upper screen of the NoVOCs™ well were calculated using an electronic spreadsheet following the procedures above. Groundwater level data for wells MW-48, MW-49, MW-52, and MW-53 were recorded in 15-second intervals; therefore, calculation procedures for the mean elevation were further modified to use all the data that had been collected. The principle of this modification is the same as discussed above.

The mean groundwater elevations calculated for wells MW-45, MW-48, MW-52, and the upper screen of the NoVOCs™ well represent groundwater flow patterns in the upper aquifer zone. The mean groundwater flow direction in the lower aquifer zone was characterized by the mean water elevation data from wells MW-47, MW-49, and MW-53. Data for other monitoring wells were not used because the wells were either constructed between the two zones or fully penetrate the aquifer. Groundwater elevation data for some of the wells are not available.

5.4.2 Density Correction of Groundwater Levels

Evaluation of groundwater flow pattern in the vicinity of the NoVOCs™ well is further complicated by seawater intrusion. The salinity of groundwater at the site is generally 2 to 3 percent and the density of groundwater samples from almost all the monitoring wells is greater than 1 gram/cubic centimeter (g/cm^3). In addition, groundwater density varies by well location and depth. In general, the density of

groundwater is higher in the lower aquifer zone. In the following sections, the calculation of equivalent fresh-water heads and the correction of groundwater levels measured by pressure transducers are discussed.

5.4.2.1 Calculation of Equivalent Fresh-Water Heads

Calculation of equivalent fresh-water heads (elevations) from an aquifer with variable water density is the first step of the density correction. Equivalent fresh-water heads plotted on maps and contoured are necessary to estimate horizontal groundwater flow direction and hydraulic gradient. The apparent head measurements in a density-variable aquifer should not be used to plot groundwater level contour maps: the contours of such plots will be misleading because the density effect can cause water to flow from apparent low to apparent high heads.

The following discussion presents the principles and procedures for calculating the equivalent fresh-water head. Density correction procedures for data collected by pressure transducer are different from those for manual measurements using water level indicators.

Groundwater hydraulic head is a sum of elevation head and pressure head, described as follows (Freeze and Cherry 1979):

$$h = z + \psi \qquad (5\text{-}36)$$

where

h	=	The hydraulic head [L]
z	=	Elevation of the point of measurement [L]
Ψ	=	The pressure head [L]

The pressure head of groundwater is a function of gage pressure and groundwater density; therefore, the hydraulic head can be further defined as follows:

$$h = z + \frac{p}{\rho g} \qquad (5\text{-}37)$$

where

p	=	Groundwater gage pressure $[ML^{-1}T^{-2}]$
ρ	=	Groundwater density $[ML^{-3}]$
g	=	Gravitational acceleration $[LT^{-2}]$

Equation 5-37 shows that the hydraulic head (h) for higher density water will be less than the hydraulic head for fresh water under the same pressure and elevation conditions. Groundwater does not necessarily flow from the higher head to the lower head under this circumstance.

From Equation 5-37, the measured groundwater elevation above the MLLW in a monitoring well at the site is as follows:

$$h = z + \frac{p}{\rho_b g} \qquad (5\text{-}38)$$

where

h	=	The measured groundwater elevation using water level indicator [L]
ρ_b	=	Density of groundwater in the well $[ML^{-3}]$
z	=	Elevation of the middle point of the well screen above (positive) or below (negative) a datum [L]
p	=	Groundwater gage pressure at the middle point of the well screen $[ML^{-1}T^{-2}]$

Also from Equation 5-37, the equivalent fresh-water head above the datum in the monitoring well is given by:

$$h^* = z + \frac{p}{\rho_0 g} \qquad (5\text{-}39)$$

where

h^*	=	Equivalent fresh water head above the datum [L]
ρ_0	=	Density of fresh water (assumed to be 1) $[ML^{-3}]$

Considering that the gage pressure of groundwater in the well is constant, Equations 5-38 and 5-39 can be combined to obtain the following equation:

$$(h^* - z)\rho_0 g = (h - z)\rho_b g \qquad (5\text{-}40)$$

Rearranging Equation 5-40 and substituting specific gravity $\gamma = \rho_b/\rho_0$ into the equation, the equivalent fresh-water head, h^*, is defined as follows:

$$h^* = \gamma h + (1 - \gamma)z \qquad (5\text{-}41)$$

where

γ = Specific gravity of the groundwater [dimensionless]

Equation 5-41 should be used to calculate equivalent fresh-water head based on the water level measurements collected manually by water level indicators. Equation 5-41 may be used for pressure transducer data under certain circumstances, as explained in the next section.

5.4.2.2 Correction of Groundwater Levels Measured by Pressure Transducer

Pressure transducers measure water pressure. The water pressure reading is usually converted by data logger software to a water head above the transducer. The conversion is usually based on the density of fresh water (Equation 5-39). If the water density differs from that of fresh water but the conversion is based on fresh water, the resulting water head value will be the fresh water equivalent head relative to the transducer. If the conversion is based on the actual density of the water (Equation 5-38), the resulting water head value will be the actual water head relative to the transducer. Correcting pressure transducer data for density effects depends on whether raw pressure data were converted to heads using fresh water density or actual water density. Correcting the data also depends on (1) the manner in which the data logger software processes the data, (2) whether initial water levels input into the data logger have been corrected for density effects, and (3) whether multiple manual water level measurements are available for the data recording period. Several cases of data handling are discussed below (data logger configurations are described in bold, followed by an explanation of corrections that should be applied):

- **Case 1: The actual density of the groundwater was measured and the data logger used actual density to convert pressure data to water head above the transducer. The initial water level, measured manually and input into the data logger, was not corrected for density effects.**

All water levels recorded by the data logger are actual water levels and not fresh-water equivalent water levels. Equation 5-41 should be used to convert all water level data output from the data logger.

- **Case 2: The actual density of the groundwater was measured. The initial water level (manually measured) was corrected to a fresh-water equivalent using Equation 5-41 and input into the data logger. The data logger used fresh-water density to convert pressure to fresh-water equivalent head above the transducer. The data logger was set up to record changes from the initial water level.**

  No additional density correction is required. All data logger output will be fresh-water equivalent water levels.

- **Case 3: Actual density of groundwater was not considered in the data logger configuration. Multiple manual measurements of water levels were collected during the recording period.**

  Using the manual measurements, which represent the apparent groundwater elevations, the pressure transducer data should be adjusted to also represent apparent groundwater elevations. Equation 5-41 can then be applied to the entire adjusted data set to obtain equivalent fresh-water elevations.

- **Case 4: Actual density of groundwater was not considered in the data logger configuration. Only initial manual measurement of water levels was collected during the recording period.**

  The change in water level from the initial data point should be calculated for each pressure transducer data point. The initial pressure transducer data point should be adjusted to represent the apparent water level elevation based on the initial manual water level measurement. Equation 5-41 should be applied to the adjusted initial groundwater elevation to obtain the initial fresh-water equivalent elevation. No density correction is needed for the water-level changes calculated from the pressure transducer data. The water-level changes should be directly added to or subtracted from the density-corrected initial groundwater elevation to obtain fresh-water equivalent elevations for the entire data set.

5.4.3 Corrected Water Levels and Horizontal Groundwater Flow Direction

Groundwater elevations and drawdown changes were measured using pressure transducers during the various phases of the aquifer tests. Manual water level measurements were also collected at the pumping well and at most observation wells during the tests. The data were corrected following the procedures specified for the Case 3 and Case 4 examples discussed in the previous section. The corrected results are presented in Appendixes C through G.

Static groundwater levels were corrected for tidal influence following the procedures discussed in Section 5.4.1. Mean groundwater elevations for the upper aquifer zone were calculated using the upper screen of NoVOCs™ well and the three upper zone NoVOCs™ observation wells (MW-45, MW-48, and MW-52). Mean groundwater elevations for the lower aquifer zone were calculated using the three lower zone NoVOCs™ observation wells (MW-47, MW-49, and MW-53). The mean groundwater elevations after tidal correction are listed in Table 5-8.

The equivalent fresh-water heads of the mean groundwater elevations were calculated following the procedures discussed in Section 5.4.2. The first step of the calculation is to obtain density data for various monitoring well locations and aquifer depths because the groundwater density was not directly measured. Jacobs Engineering Group, Inc. (1995b) applied an empirical equation developed by de Marsily (1986) to calculate groundwater density from total dissolved solids (TDS) data. The empirical equation was developed based on a laboratory test with sodium chloride solution and a linear regression analysis.

The empirical equation developed by de Marsily (1986) is as follows:

$$\rho = (\ 6.87 \times 10^{-4}\ C_{TDS}\ ) + 998.4575 \qquad (5\text{-}42)$$

where

ρ	=	Groundwater density (kg/m³)
C_{TDS}	=	TDS concentration (mg/L)

The groundwater density and results for equivalent fresh-water head calculation are presented in Table 5-8.

The mean equivalent fresh-water head contours for the upper aquifer zone are plotted in Figures 5-33 and 5-34. Figure 5-33 is based on four points (including data for well MW-48), and Figure 5-34 is based on three points (excluding data for well MW-48). The two presentations (with and without data for well MW-48 data) are provided because the screen of well MW-48 is at a lower elevation than in the other three wells used to construct the contours. The mean equivalent fresh-water head contours for the lower aquifer zone are plotted in Figure 5-35. These contour maps represent the mean static water levels and flow directions with tidal and pumping influences removed. Effects caused by variation in groundwater

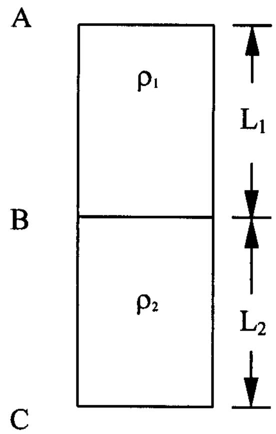
density variation were also corrected. These contour maps are considered representative of the natural groundwater flow pattern.

As shown in Figures 5-33, 5-34, and 5-35, groundwater generally flows to the west or northwest in both of the upper and lower aquifer zones. The horizontal hydraulic gradient in both aquifer zones is relatively flat, ranging from 0.005 to 0.01 feet per feet in the upper zone and approximately 0.006 in the lower zone. Data for generating the contour maps were limited (four points for the upper aquifer zone and three points for the lower aquifer zone) because other NoVOCs™ observation wells were completed at depths between the two aquifer zones. Also, data were not available for some of the observation wells because of data logger malfunction.

5.4.4 Vertical Hydraulic Gradient Correction

Calculation of vertical hydraulic gradient in a fresh-water aquifer (groundwater density of 1 g/cm^3) is simple: for two vertically aligned wells, the vertical hydraulic gradient equals the head difference between the wells divided by the distance between the midpoint of the well screen intervals. However, calculation of vertical hydraulic gradient in a density-variable aquifer is relatively complex. Incorrect calculations of the vertical hydraulic gradient by simply using equivalent fresh-water heads to determine the head difference are common. The vertical hydraulic gradient in a density-variable aquifer is a function of the equivalent fresh-water heads, the distance between the two intervals, and the groundwater density. This section discusses the principles and the reason for calculating vertical hydraulic gradient differently from the horizontal hydraulic gradient. The procedures to calculate the vertical hydraulic gradient in a density-variable aquifer are also presented.

Vertical hydraulic gradient is not calculated in this report because limited groundwater density data are available. Also, vertical hydraulic gradient was not identified as a key parameter in the pumping test data analysis and NoVOCs™ well evaluation. The equations and procedures discussed in this section can be followed in future data analysis for the vertical hydraulic gradient at the site.



Considering water column ABC filled with a porous medium as shown in the Drawing: the upper portion, AB, has a height L_1 and contains water (or any fluid) with a density equal to ρ_1; the lower portion, BC, has a height of L_2 and contains water with a density equal to ρ_2. Water in the column is assumed to be in a hydraulic steady state, that is, no vertical flow occurs. Vertical hydraulic gradient is to zero between any two points within the column. Also, it is assumed that no density-driven flow and no density diffusion occur across the boundary line B.

If the bottom of the column is set at the datum, that is, the elevation z equals zero at point C, from Equation 5-39, the equivalent fresh water-head at the three points (A, B, and C) will be given as:

$$h_A^* = z_A + \frac{p_A}{\rho_0 g} \tag{5-43}$$

$$h_B^* = z_B + \frac{p_B}{\rho_0 g} \tag{5-44}$$

$$h_C^* = z_C + \frac{p_C}{\rho_0 g} \tag{5-45}$$

where

p_A, p_B, and p_C	=	The groundwater pressure gages at points A, B, and C
z_A, z_B, and z_C	=	The elevations of points A, B, and C

Equations 5-43, 5-44, and 5-45 can be solved as follows, considering p_A=0, p_B=$\rho_1 g L_1$, p_C=$\rho_1 g L_1$+$\rho_2 g L_2$, z_A=L_1+L_2, z_B=L_2, and z_C=0:

$$h_A^* = (L_1 + L_2) + 0 = L_1 + L_2 \tag{5-46}$$

$$h_B^* = L_2 + \frac{\rho_1 g L_1}{\rho_0 g} = \gamma_1 L_1 + L_2 \quad (5\text{-}47)$$

$$h_C^* = 0 + \frac{(\rho_1 L_1 + \rho_2 L_2) g}{\rho_0 g} = \gamma_1 L_1 + \gamma_2 L_2 \quad (5\text{-}48)$$

Because $\gamma_1 \neq \gamma_2 \neq 1$, Equation 5-46, 5-47, and 5-48 show that the equivalent fresh-water heads at the three points are not equal. This result contradicts the assumption that no vertical flow occurs in the water column. Therefore, the difference in the two equivalent fresh-water heads divided by the distance between the two points does not equal the vertical hydraulic gradient in aquifers with variable density groundwater.

In general, the vertical hydraulic gradient between two vertically aligned points within variable density groundwater equals the difference of the fresh-water equivalent heads at the two points divided by the distance plus a constant. That is:

$$I_{AB} = \frac{h_A^* - h_B^*}{L_1} + C_1 \quad (5\text{-}49)$$

$$I_{BC} = \frac{h_B^* - h_C^*}{L_2} + C_2 \quad (5\text{-}50)$$

$$I_{AC} = \frac{h_A^* - h_C^*}{L_1 + L_2} + C_3 \quad (5\text{-}51)$$

where

I_{AB} = Vertical hydraulic gradient between points A and B.

I_{BC} = Vertical hydraulic gradient between points B and C.

I_{AC} = Vertical hydraulic gradient between points A and C.

From Equations 5-46, 5-47, and 5-48, considering $I_{AB} = I_{BC} = I_{AC} = 0$, for steady state condition, we can solve C_1, C_2 and C_3 as:

$$C_1 = \frac{h_B^* - h_A^*}{L_1} = \frac{\gamma_1 L_1 + L_2 - (L_1 + L_2)}{L_1} = \gamma_1 - 1 \tag{5-52}$$

$$C_2 = \frac{h_C^* - h_B^*}{L_2} = \frac{\gamma_1 L_1 + \gamma_2 L_2 - (\gamma_1 L_1 + L_2)}{L_2} = \gamma_2 - 1 \tag{5-53}$$

$$C_3 = \frac{h_C^* - h_A^*}{L_1 + L_2} = \frac{\gamma_1 L_1 + \gamma_2 L_2 - (L_1 + L_2)}{L_1 + L_2} = \frac{\gamma_1 L_1 + \gamma_2 L_2}{L_1 + L_2} - 1 \tag{5-54}$$

Therefore, vertical hydraulic gradient between any two points in an aquifer with density-variable groundwater can be calculated using the following general equation (based on Equations 5-49 through 5-54):

$$I_V = \frac{h_u^* - h_l^*}{l} + (\gamma - 1) \tag{5-55}$$

where

I_V = Vertical hydraulic gradient between two vertically aligned points within the aquifer (positive value represents downward gradient) [dimensionless]

h_u, h_l = The equivalent fresh water heads at the two points (higher elevation and lower elevation points, respectively) [L]

l = Vertical distance between the two points [L]

γ = Specific gravity of groundwater between the two points [dimensionless]

The specific gravity of groundwater between the two points should be carefully chosen when Equation 5-55 is used. If the groundwater density is not constant between the upper and lower aquifer zones, a thickness-weighted average of the specific gravity for multiple density strata should be used. The weighted average of the specific gravity is calculated as follows:

$$\gamma = \frac{\sum_{i=1}^{n} \gamma_i l_i}{\sum_{i=1}^{n} l_i}, \qquad i = 1,2,\ldots n \tag{5-56}$$

where

γ	=	The weighted average of the specific gravity of groundwater
γ_i	=	The specific gravity of the i^{th} strata
l_i	=	The thickness of the i^{th} strata

5.5 DIPOLE FLOW TEST

The dipole flow test (DFT), a new single-well hydraulic test for aquifer characterization, was first proposed by Kabala (1993). The test was designed to characterize the vertical distribution of local horizontal and vertical hydraulic conductivities near the test well. Measures of the aquifer's anisotropy ratio and storativity can also be obtained through DFT data analysis. DFT is a cost-effective method for aquifer hydraulic characterization because (1) the test duration is short; the test generally lasts no more than a few hours, and (2) no investigation-derived waste is generated because the water from the pumping chamber is injected to the aquifer through recharge chamber.

5.5.1 Mathematical Models

Kabala (1993) presented a mathematical model describing drawdown (or water level rise) during a dipole flow test in each of the isolated chambers of a well situated in a leaky homogeneous anisotropic aquifer. Major assumptions for this original model are:

- The aquifer is homogeneous and anisotropic and horizontally situated
- The aquifer is under either leaky or confined conditions
- The test well fully penetrates the aquifer thickness
- Water is removed through one of the two open screened intervals and discharged to another interval instantaneously
- Linear vertical head distribution is assumed in the semiconfining layer (leaky aquitard)

- Water storage in the leaky aquitard is negligible
- Flows in the aquifer zones are mainly horizontal, but primarily vertical mithin the leaky aquitard
- Well bore storage and well losses are insignificant
- "Skin effect" (short-circuiting through the sand packs) is negligible

The analytical solutions for drawdown in the pumping chamber and water level rise in the recharge chamber are presented by Kabala (1993). The transient solution describing drawdown is given as follows:

$$s(t)=\frac{Q}{4\pi K_r b}\{W(u_r;\beta_w) + \frac{2b^2}{4\pi^2\Delta^2}\sum_{n=1}^{\infty}\frac{1}{n^2}[\sin\frac{n\pi(d+2\Delta)}{b}-\sin\frac{n\pi d}{b}]^2 W[u_r;(\beta_w{}^2+\frac{(n\pi r_w)^2}{a^2b^2})^{1/2}\} \qquad (5\text{-}57)$$

where

s(t)	=	Drawdown in the pumping chamber [L]
t	=	Time since beginning of the test [L]
Q	=	Pumping rate $[L^3T^{-1}]$
K_r	=	Horizontal hydraulic conductivity $[LT^{-1}]$
b	=	Aquifer thickness [L]
d	=	Distance from the top of aquifer to the top of the upper chamber [L]
Δ	=	Half of the length of the screen interval [L]
a^2	=	Aquifer anisotropy ratio, defined as K_r/K_z [dimensionless]
$W(u_r, \beta_w)$	=	Leaky aquifer well function, defined as:

$$W(u_r;\beta_w)=\int_{u_r}^{\infty}\frac{1}{y}\exp(-y-\frac{\beta_w{}^2}{4y})dy \qquad (5\text{-}58)$$

where

u_r	=	Dimensionless time, defined as: $r_w{}^2 S_s/4K_rt$
β_w	=	Leaky factor defined as: $r_w/(K_rbb'/K')^{1/2}$
r_w	=	Radius of the well casing [L]
S_s	=	Aquifer specific storage $[L^{-1}]$

b'	=	Aquitard (semi-confining layer) thickness [L]
K'	=	Aquitard vertical hydraulic conductivity [LT^{-1}]

A similar solution can be derived to describe water level rise due to injection in the recharge chamber with a negative pumping rate. Combining the pumping and injection effects, the actual drawdown in the pumping chamber is given by:

$$s(t) = \frac{Q}{\pi K_r b}\sum_{n=1}^{\infty}\left[\frac{\sin(n\pi\Delta/b)}{n\pi\Delta/b}\right]^2 \cdot \sin(n\pi\frac{l+d}{2b})\sin(n\pi\frac{l-d-2\Delta}{2b})\cos(n\pi\frac{d+\Delta}{b})\cdot W[u_r;(\beta_w{}^2+\frac{(n\pi r_w)^2}{a^2b^2})^{1/2}] \qquad (5\text{-}59)$$

The solution for actual water level rise in the recharge chamber is given by:

$$s(t) = \frac{Q}{\pi K_r b}\sum_{n=1}^{\infty}\left[\frac{\sin(n\pi\Delta/b)}{n\pi\Delta/b}\right]^2 \cdot \sin(n\pi\frac{l+d}{2b})\sin(n\pi\frac{l-d-2\Delta}{2b})\cos(n\pi\frac{l-\Delta}{b})\cdot W[u_r;(\beta_w{}^2+\frac{(n\pi r_w)^2}{a^2b^2})^{1/2}] \qquad (5\text{-}60)$$

Equations (5-59) and (5-60) are the transient solutions for the dipole flow test. The steady state solution for drawdown in the pumping chamber is as follows:

$$s(t) = \frac{2Q}{\pi K_r b}\sum_{n=1}^{\infty}\left[\frac{\sin(n\pi\Delta/b)}{n\pi\Delta/b}\right]^2 \cdot \sin(n\pi\frac{l+d}{2b})\sin(n\pi\frac{l-d-2\Delta}{2b})\cos(n\pi\frac{d+\Delta}{b})\cdot K_0[(\beta_w{}^2+\frac{(n\pi r_w)^2}{a^2b^2})^{1/2}] \qquad (5\text{-}61)$$

Where

K_0	=	Zero-order modified Bessel function of the second kind,
l	=	Distance from the top of the aquifer to the bottom of the lower screen.

5.5.2 Modified Dipole Flow Test Solution for Wellbore Storage

Kabala (1998) developed a new DFT model to account for wellbore storage effects in the pumping and injection chambers. In the wellbore storage DFT model, measured drawdown (or water level rise) is the

sum of aquifer drawdown and wellbore storage drawdown. Dimensionless wellbore storage parameters for the pumping and recharge chambers are defined as:

$$C_{PD} = \frac{(r_i / r_w)^2}{4S} \tag{5-62}$$

$$C_{RD} = \frac{1-(r_i / r_w)^2}{4S} \tag{5-63}$$

where

C_{PD}	=	Dimensionless wellbore storage parameter for the pumping chamber
C_{RD}	=	Dimensionless wellbore storage parameter for the recharge chamber
r_i	=	Radius of inner well casing (eductor pipe)[L]
r_w	=	Radius of well casing [L]
S	=	Aquifer storativity or specific yield [dimensionless]

Laplace transformation is used to solve the partial differential equations that describe drawdown (or water level rise) in the pumping (or recharge) chamber during the DFT where the wellbore storage effect is considered. The drawdown in the pumping chamber s_{pump} can be described as:

$$s_{pump}(p) = s_{pp}(p) + s_{pi}(p) \tag{5-64}$$

where p is the Laplace transformation variable, s_{pp} (p) is the drawdown caused by pumping, and s_{pi} (p) is the water level caused by injection (expressed as negative drawdown). The two components of the water level response are defined as follows:

$$s_{pp}(p) = \frac{Q}{4\pi K_r b} \cdot \frac{\frac{2}{p} K_0(\sqrt{p}) + 4\sum_{n=1}^{\infty} \frac{\alpha_n^{\,2}}{p} K_0(\sqrt{p+\gamma_n^{\,2}})}{C_{PD} p^2 [\frac{2}{p} K_0(\sqrt{p}) + 4\sum_{n=1}^{\infty} \frac{\alpha_n^{\,2}}{p} K_0(\sqrt{p+\gamma_n^{\,2}})] + 1} \tag{5-65}$$

and

$$s_{pi}(p) = \frac{-Q}{4\pi K_r b}$$

$$\cdot \left\{1 - \frac{[\frac{2}{p}K_0(\sqrt{p}) + 4\sum_{n=1}^{\infty}\frac{\beta_n^2}{p}K_0(\sqrt{p+\gamma_n^2})][\frac{2}{p}K_0(\sqrt{p}) + 4\sum_{n=1}^{\infty}\frac{\alpha_n^2\beta_n^2}{p}K_0(\sqrt{p+\gamma_n^2})]}{C_{RD}p^2[\frac{2}{p}K_0(\sqrt{p}) + 4\sum_{n=1}^{\infty}\frac{\beta_n^2}{p}K_0(\sqrt{p+\gamma_n^2})] + 1}\right\} \quad (5\text{-}66)$$

Variables α_n, β_n, and γ_n are defined as follows:

$$\alpha_n = \frac{b}{n\pi\Delta_u}\cdot\sin(\frac{n\pi\Delta_u}{b})\cdot\cos[\frac{n\pi(d+\Delta_u)}{b}] \quad (5\text{-}67)$$

$$\beta_n = \frac{b}{n\pi\Delta_l}\cdot\sin(\frac{n\pi\Delta_l}{b})\cdot\cos[\frac{n\pi(l-\Delta_l)}{b}] \quad (5\text{-}68)$$

$$\gamma_n = \frac{n\pi r_w}{b\sqrt{K_r / K_z}} \quad (5\text{-}69)$$

where:

Δ_u	=	Half of the upper screened interval [L]
Δ_l	=	Half of the lower screened interval [L]

5.5.3 Dipole Flow Test Data Interpretation and Aquifer Anisotropy Estimation

The dimensionless drawdown in the pumping chamber versus dimensionless time can be plotted as groups of type curves with different anisotropy ratios ($a^2 = K_r/K_z$) and storativity (or specific yield) values. The type curves are generated by plotting dimensionless drawdown s_D versus dimensionless time τ, which are defined as follows:

$$s_D = \frac{s(t)}{s(\infty)} \quad (5\text{-}70)$$

and

$$\tau = \frac{\nu t}{r_w^{\;2}} \qquad (5\text{-}71)$$

where

$s(\infty)$	=	Steady state drawdown or water level rise during the DFT [L]
ν	=	Aquifer hydraulic diffusivity, defined as T/S or K_r/S_s [L^2T^{-1}]

Drawdown (or water level rise) data collected during the DFT then be normalized to dimensionless drawdown (or water level rise) with values ranging from 0 to 1, as follows:

$$s_D(t) = \frac{s(t+t_0) - s_{\min}}{s_{\max} - s_{\min}} \qquad (5\text{-}72)$$

where

$s_D(t)$	=	Normalized dimensionless drawdown (or water level rise)
$s(t+t_0)$	=	Drawdown (or water level rise) at time $t+t_0$ [L]
t_0	=	The beginning time of a given step of the DFT [T]
s_{max}	=	The maximum drawdown (or water level rise) during a given step of the DFT [L]
s_{min}	=	The minimum drawdown (or water level rise) during a given step of the DFT [L]

The normalized drawdown or water level rise versus time are plotted for the type curve match. A scale factor (A) is applied to the real-time plots. The scale factor is applied for two purposes: (1) transferring real time to dimensionless time so the horizontal axes of the type curves and test data are comparable, and (2) adjusting the horizontal positions of the data plots so that a best match to one of the type curves can be obtained. The scale factor is defined as:

$$A = \frac{\nu}{r_w^{\;2}} = \frac{K_r}{S_s r_w^{\;2}} \qquad (5\text{-}73)$$

From the type curve match, the aquifer anisotropy ratio is obtained from the value of parameter a^2 (which equals K_r/K_z). In addition, aquifer horizontal hydraulic conductivity can be calculated from the values of parameters S (or S_y), and A. The aquifer horizontal hydraulic conductivity K is calculated by the following equation:

$$K_r = \frac{A \cdot r_w^{\,2} S}{b} \qquad (5\text{-}74)$$

DFT data collected during Step 4 recovery in the recharge chamber were considered the most suitable for parameter estimation because the water level rise data were least affected by variations in pumping rate variations and head fluctuations.

Tidal influence during the DFT is removed using data collected from well MW-51. Comparison of water level data from the NoVOCs™ well and observation well MW-51 shows that the tidal fluctuations in the two wells are almost identical. Well MW-51 also had minimum impact from the DFT because of its distance from the NoVOCs™ well. The least-square algorithm was used to simulate the tidal fluctuations in the NoVOCs™ well. The drawdown (or water level rise) correction procedure is similar to the procedures presented in Section 5.1.

Figure 5-36 shows the recovery data plots and type curve match for the DFT Step 4 recharge chamber. The type curves are generated using the DFT model considering well bore storage. The group of the type curves in Figure 5-36 represents storativity S=0.01 and anisotropy ratios $a^2 = K_r/K_z = 100, 30, 10, 3$, and 1. The normalized dimensionless DFT recovery data with time are represented by circles,whereas the normalized recovery data versus scaled time (dimensionless time) are plotted as thick dash line.

From the DFT recovery data plots and type curve match (Figure 5-36), the aquifer hydraulic parameters are estimated as: $K_r = 0.0115$ cm/sec, $0.001 \le S \le 0.01$, and $K_r/K_z = 4.93$. These results are very close to the parameter estimated by interpreting pumping test data (Section 5.3). The aquifer hydraulic parameters estimated through DFT are also presented in Table 5-7.

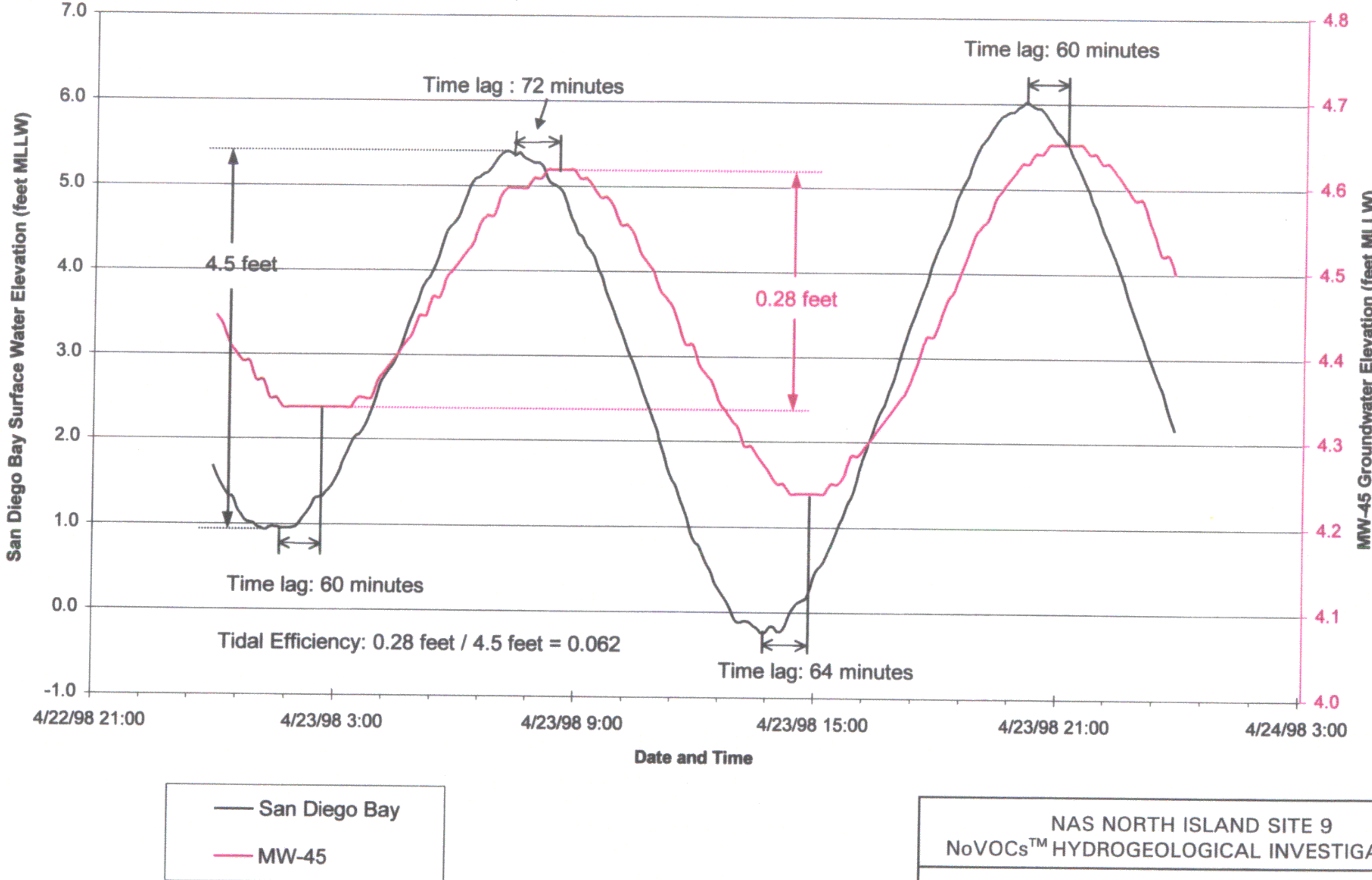


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FIGURE 5-1
WATER LEVEL COMPARISON BETWEEN SAN DIEGO BAY AND OBSERVATION WELL MW45

Tetra Tech EM Inc.

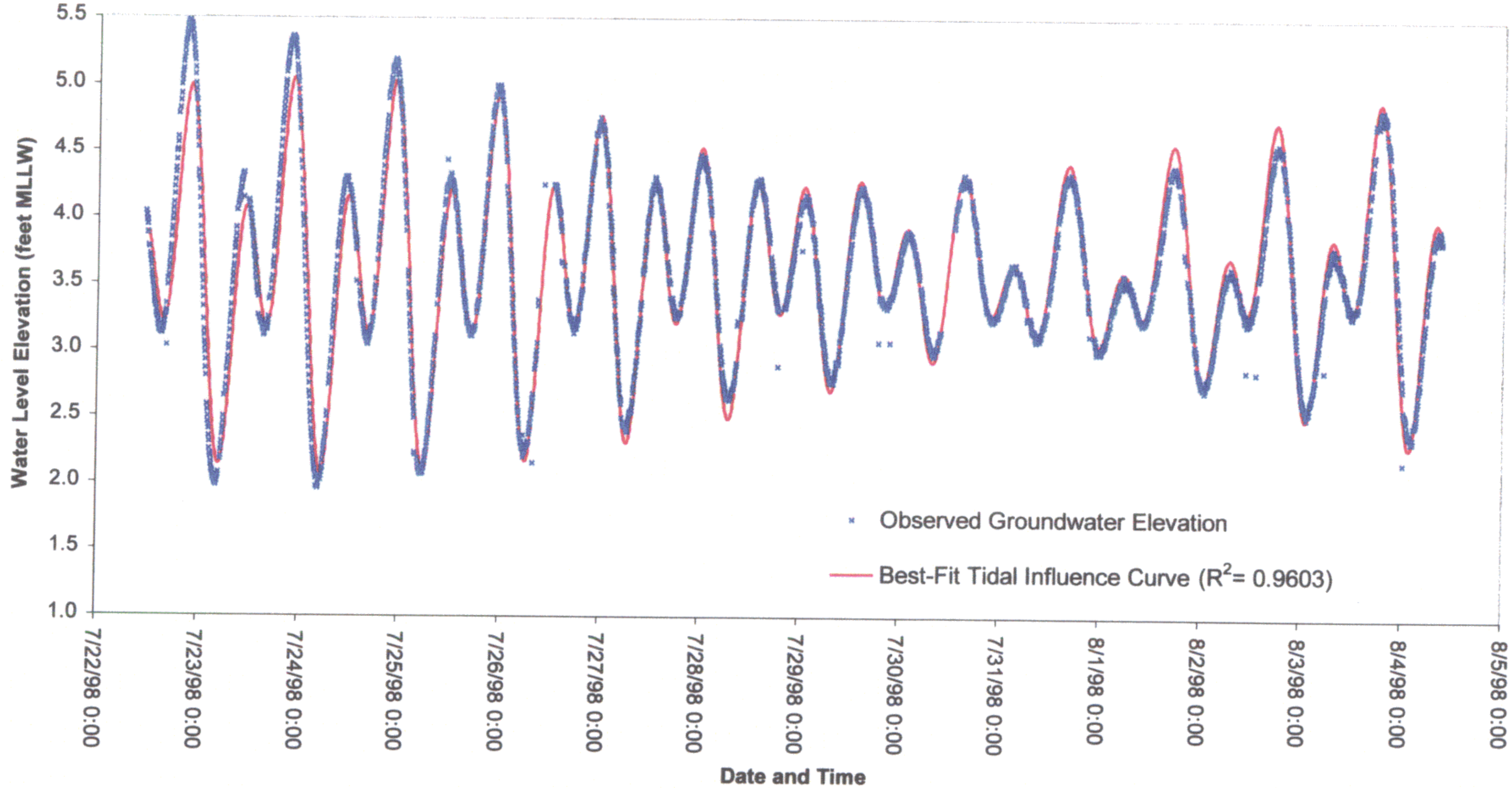

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FIGURE 5-2
OBSERVED GROUNDWATER ELEVATION AND BEST-FIT TIDAL INFLUENCE CURVE FOR WELL MW20

Tetra Tech EM Inc.

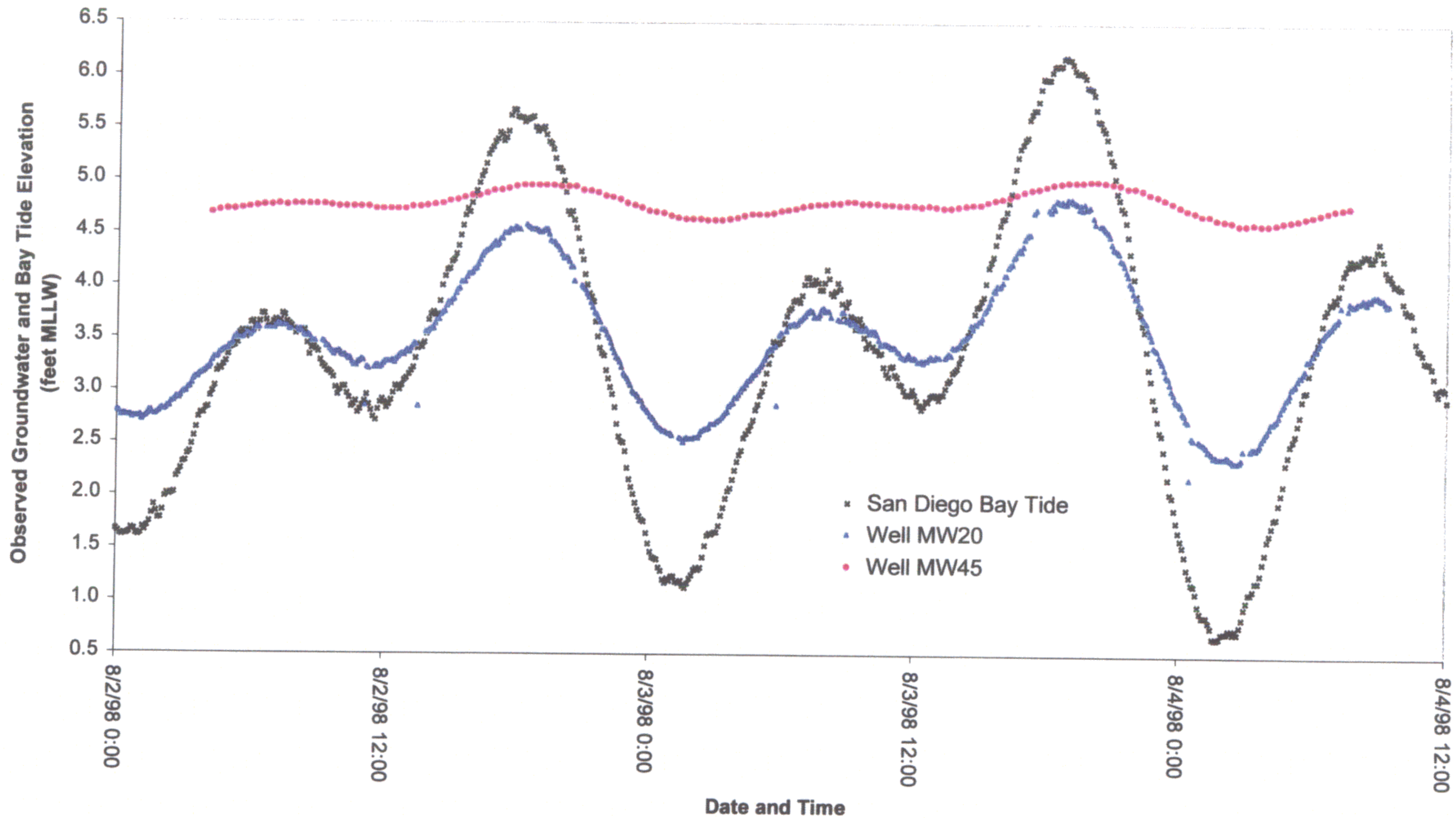

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FIGURE 5-3
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW45

Tetra Tech EM Inc.

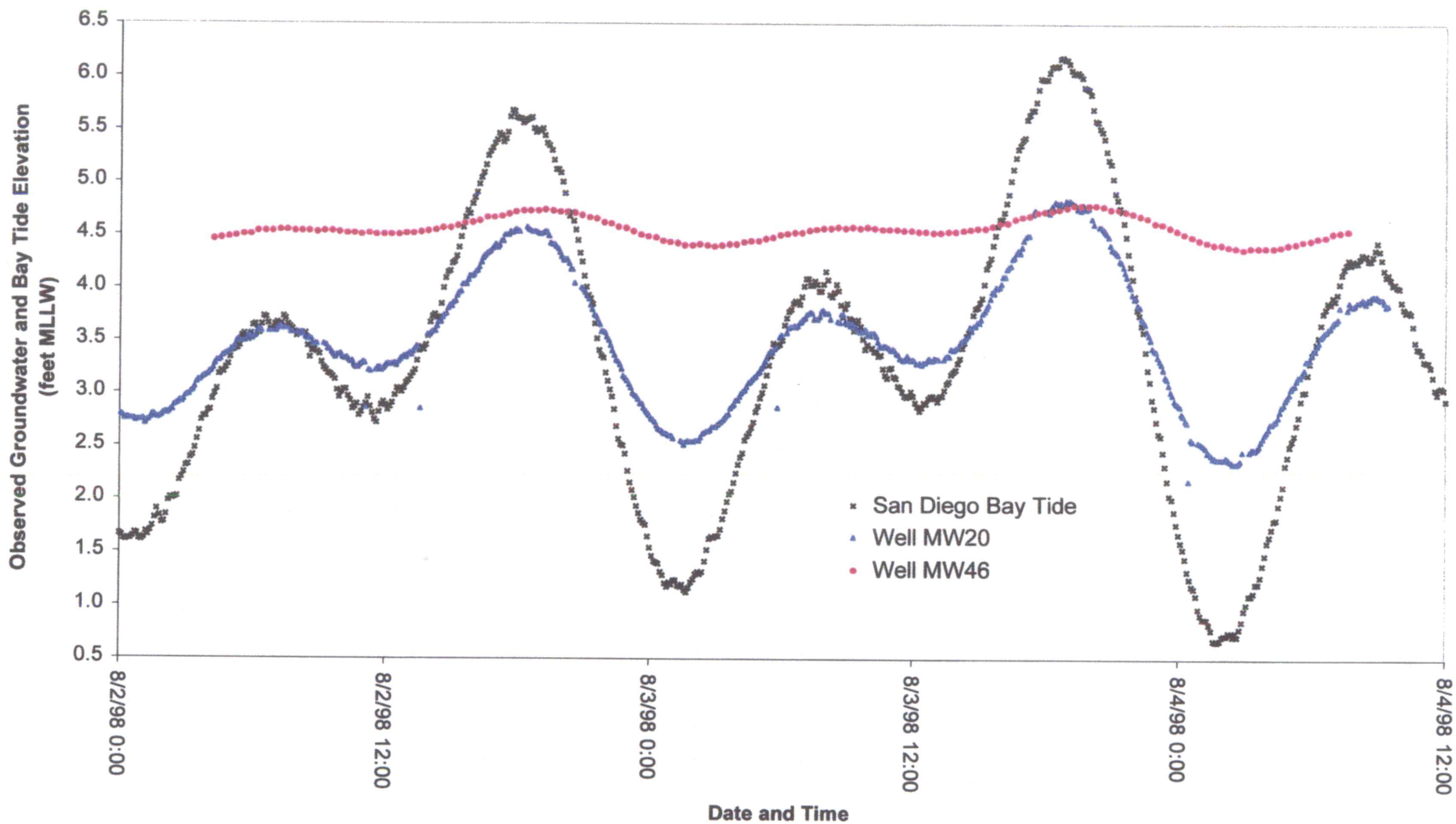

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FIGURE 5-4
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW46

Tetra Tech EM Inc.

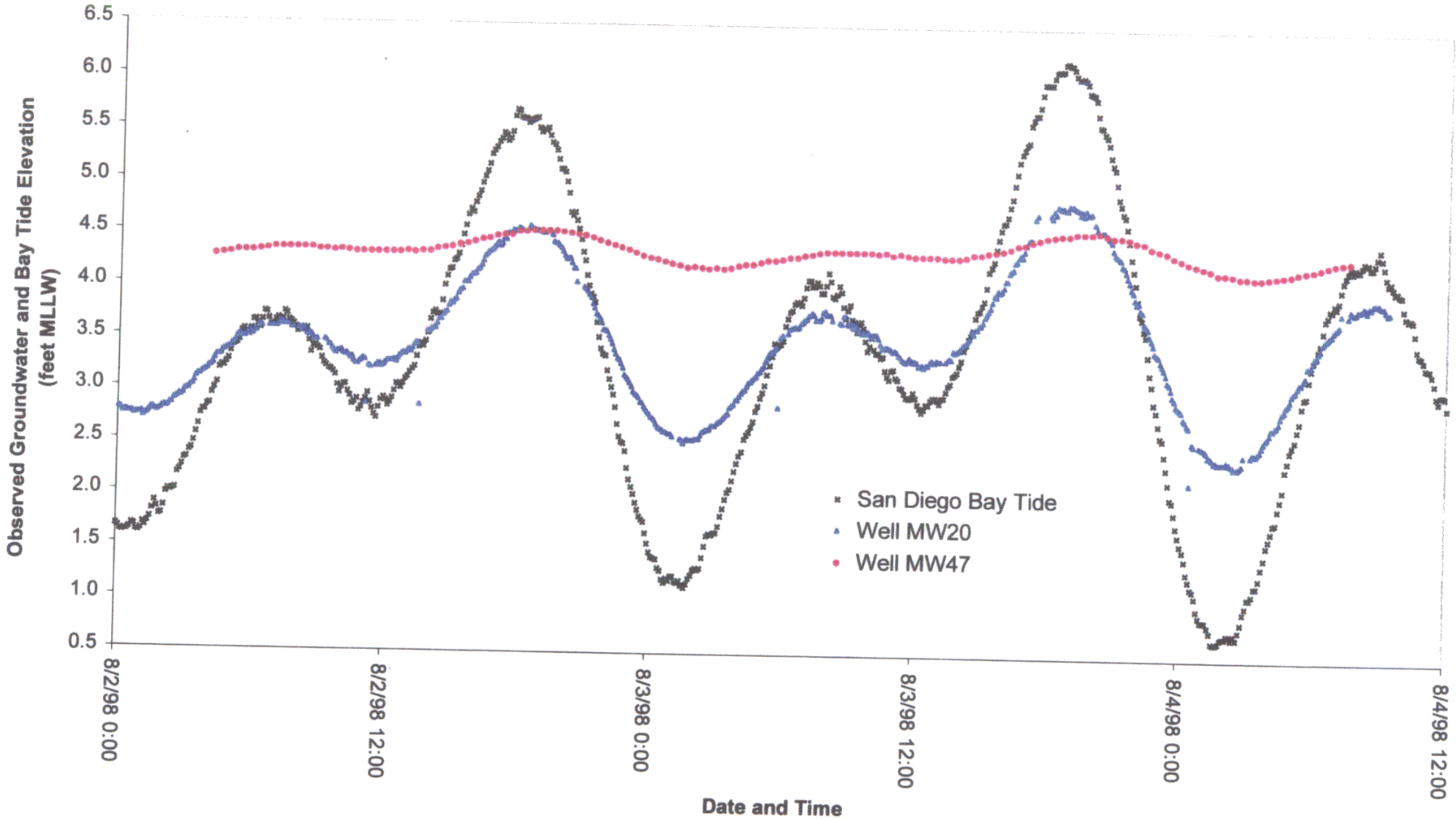

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FIGURE 5-5
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW47

Tetra Tech EM Inc.

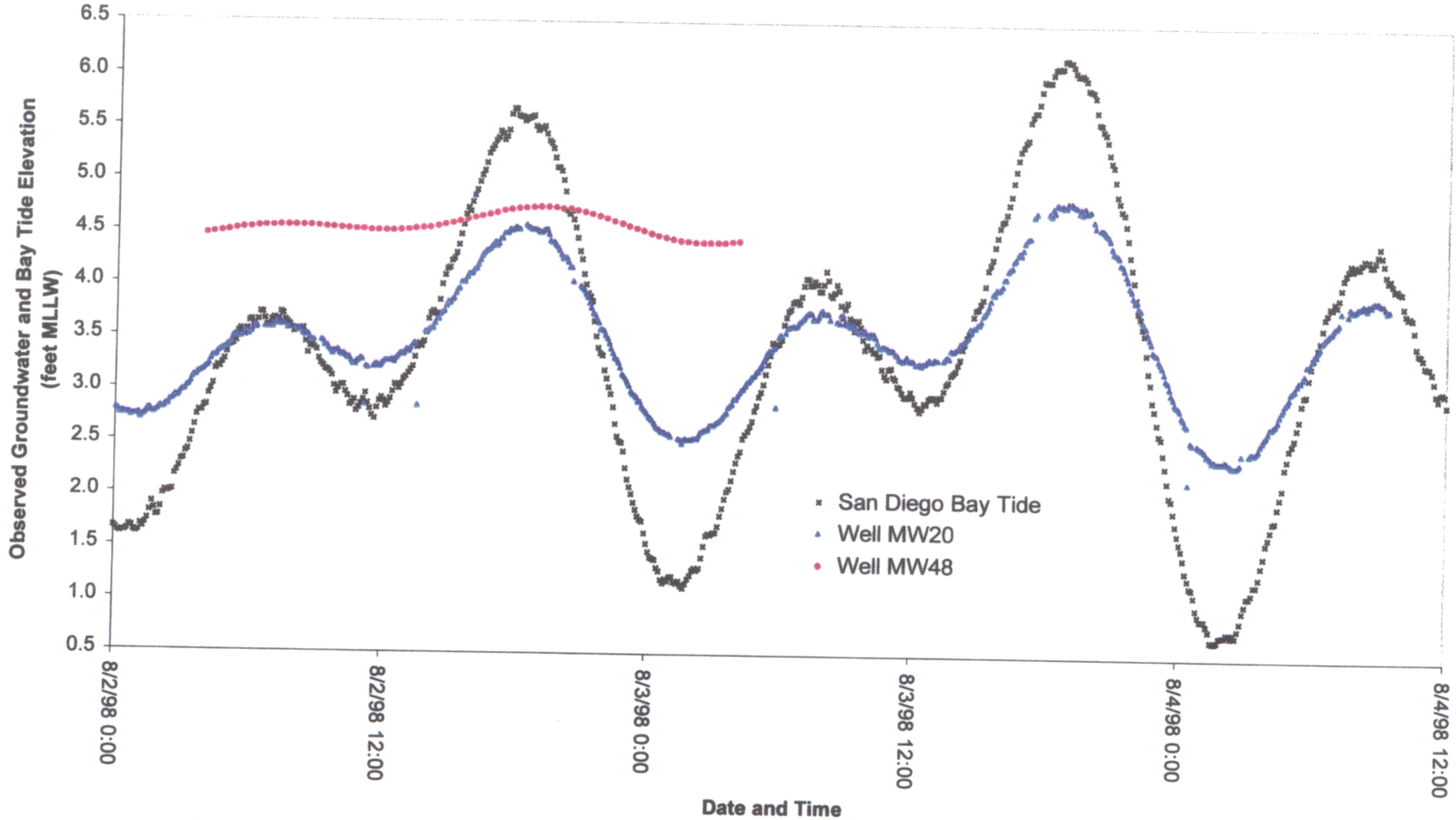

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FIGURE 5-6
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW48

Tetra Tech EM Inc.

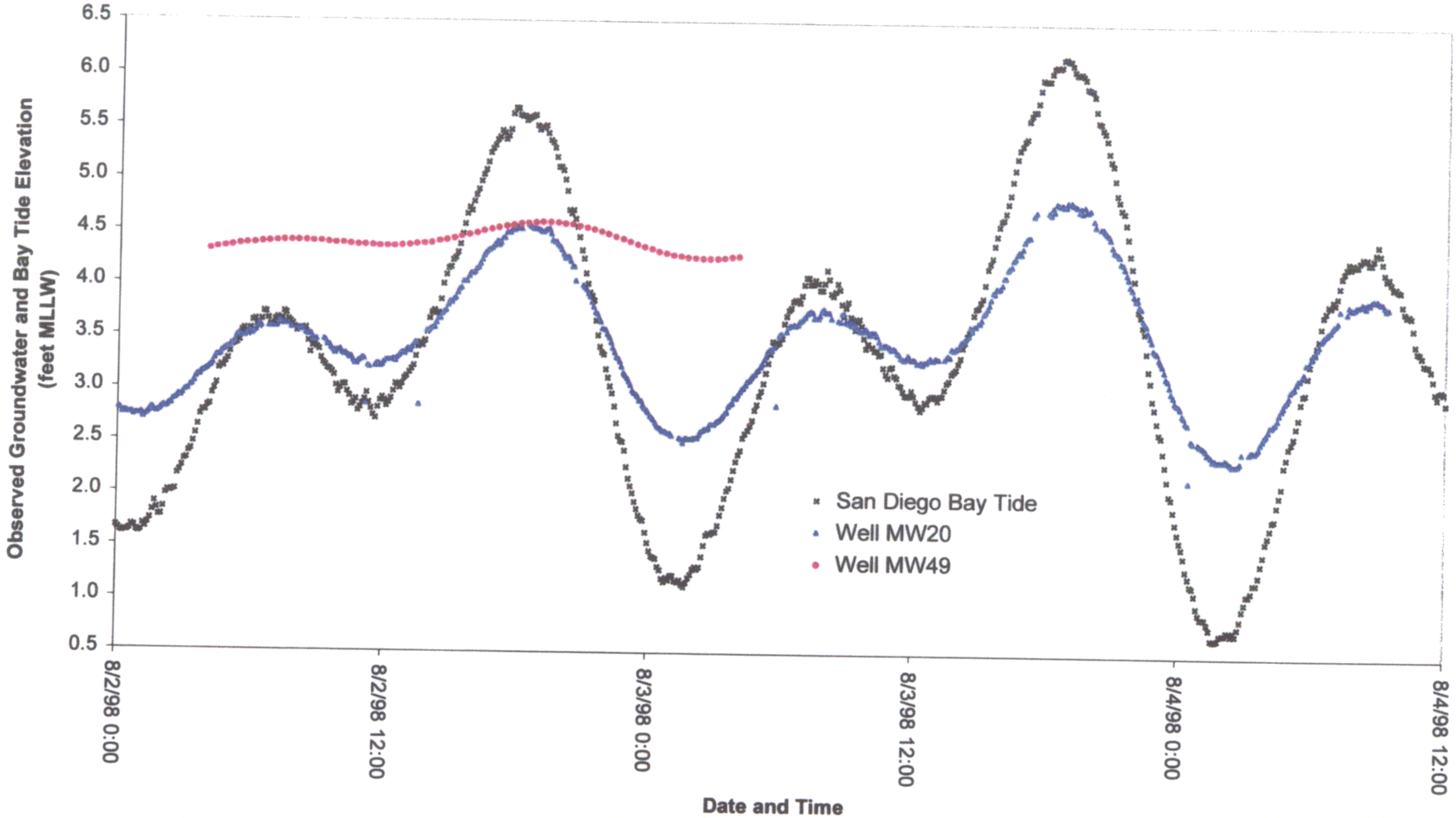

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FIGURE 5-7
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW49

Tetra Tech EM Inc.

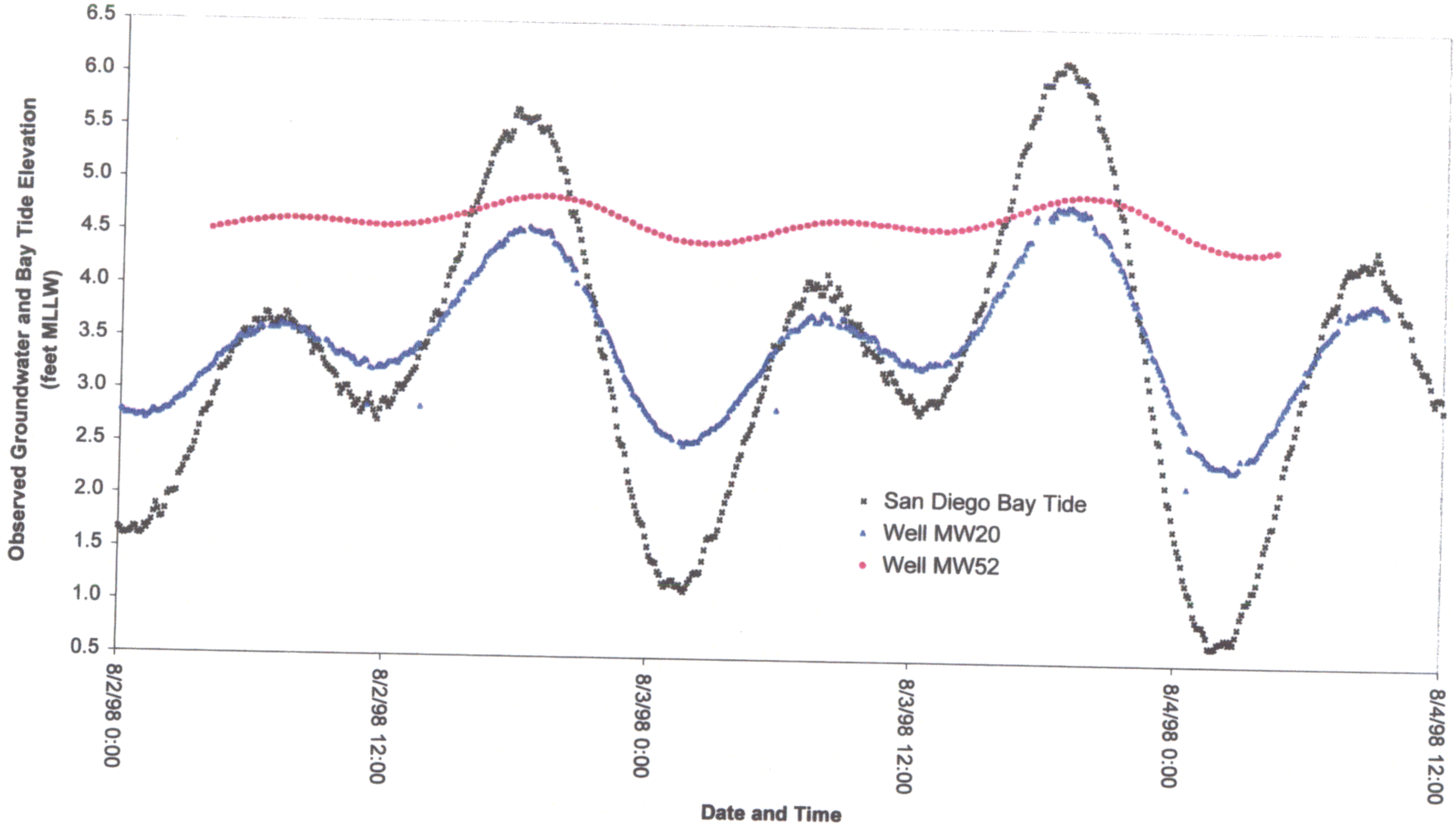

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FIGURE 5-8
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW52

Tetra Tech EM Inc.

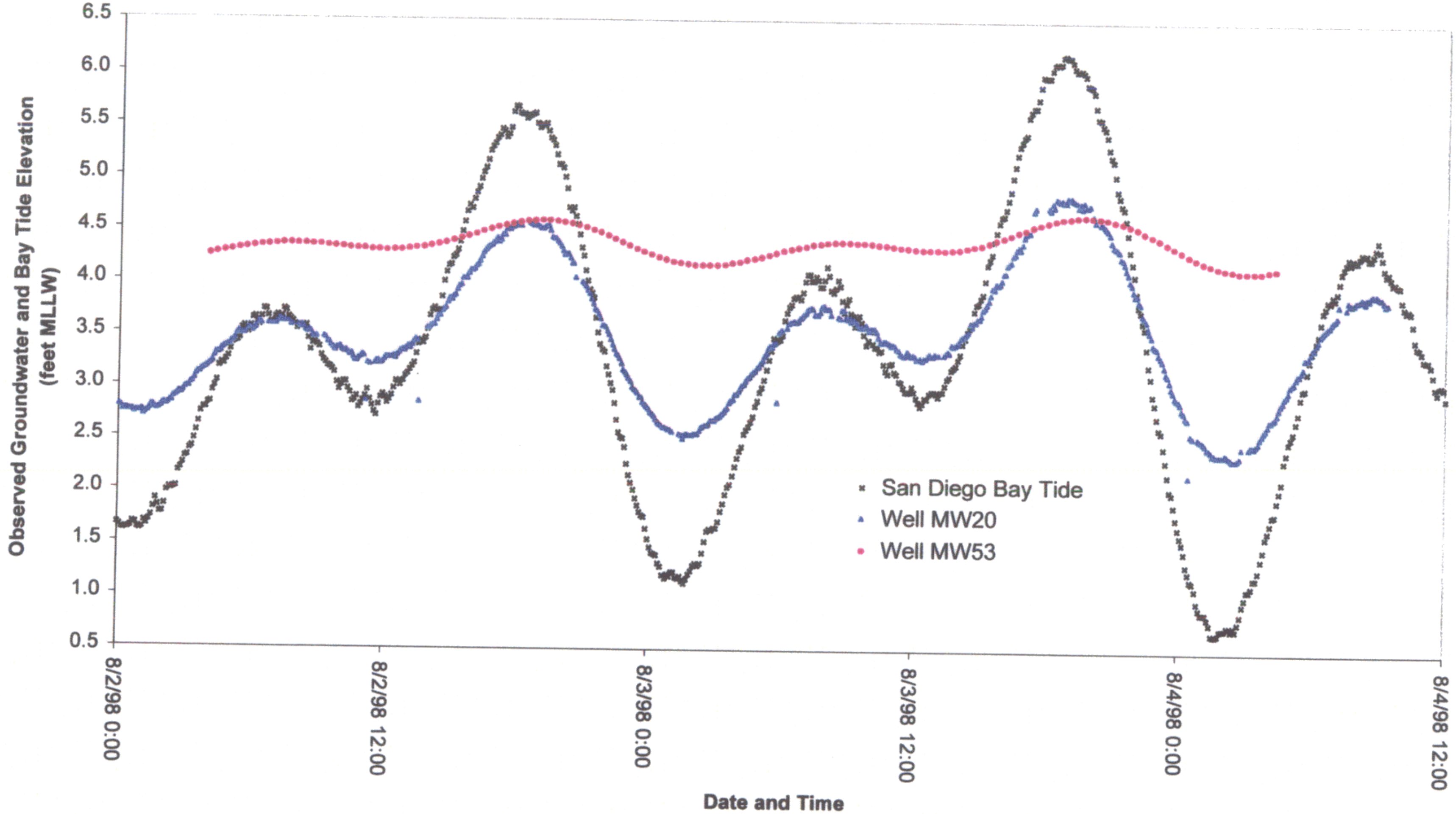

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FIGURE 5-9
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW53

Tetra Tech EM Inc.

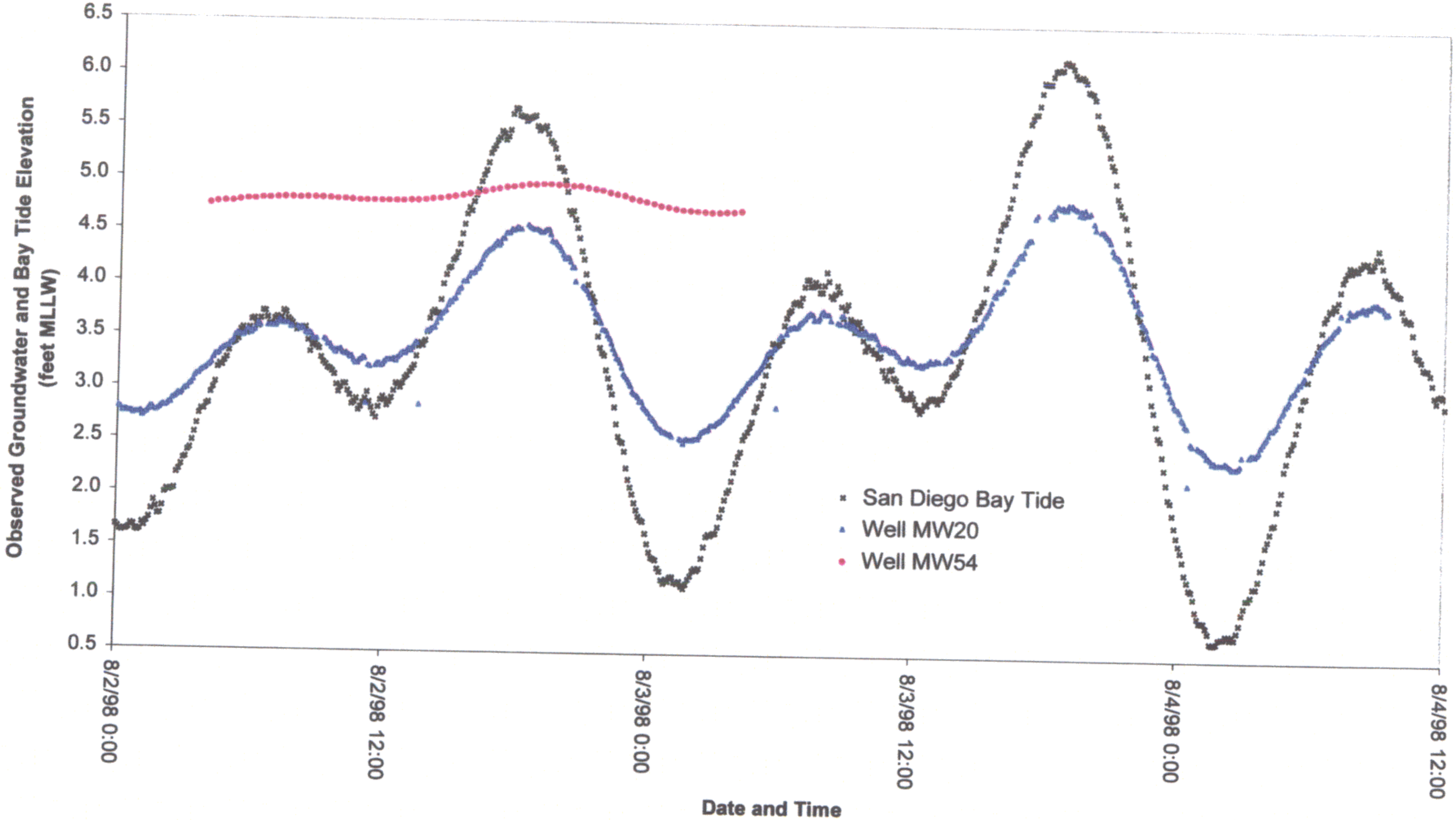

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FIGURE 5-10
OBSERVED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20 AND MW54

Tetra Tech EM Inc.

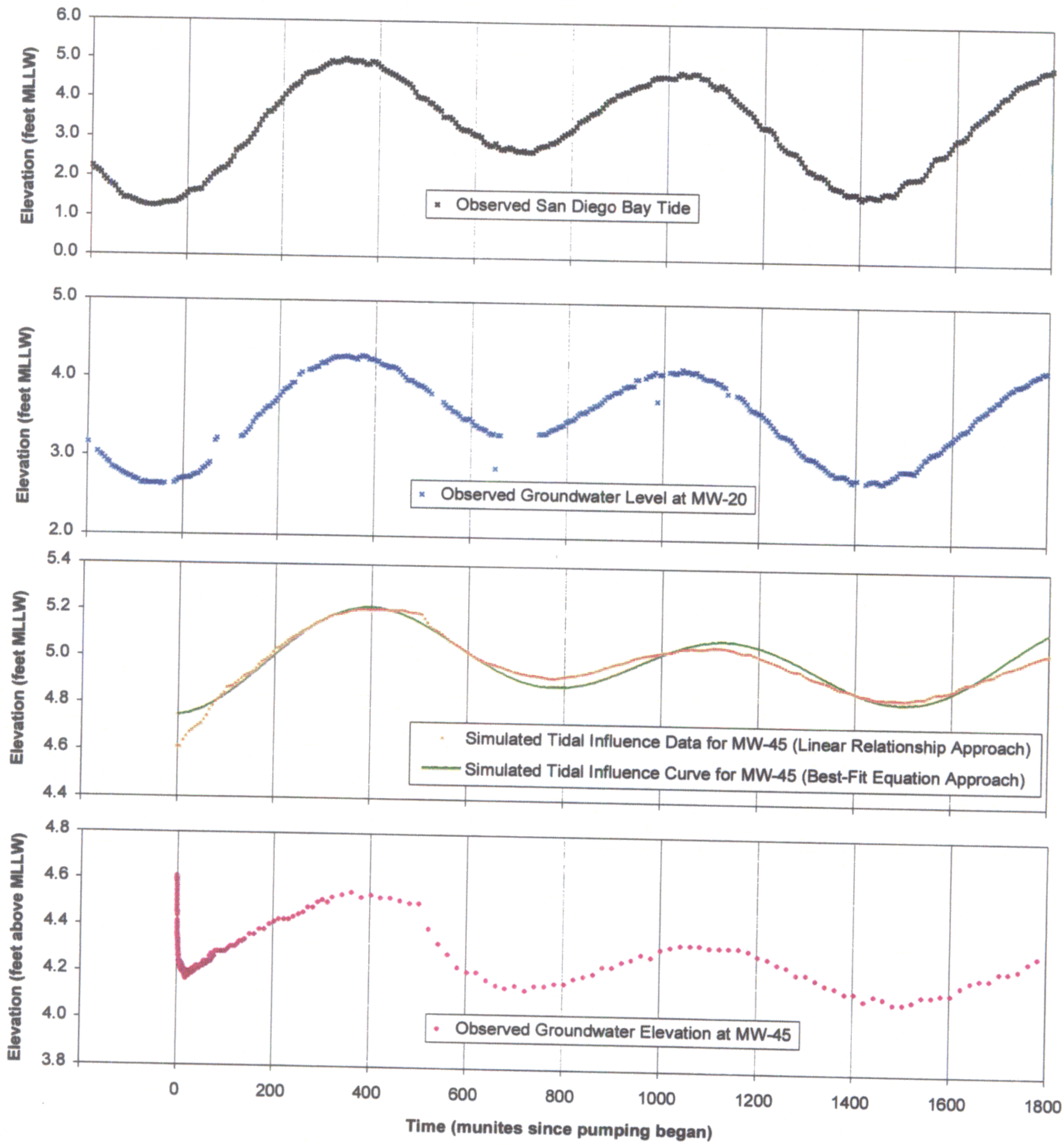

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FIGURE 5-11
OBSERVED AND SIMULATED WATER LEVEL COMPARISON AMONG BAY TIDE, MW20, MW45 DURING THE PUMPING TEST
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

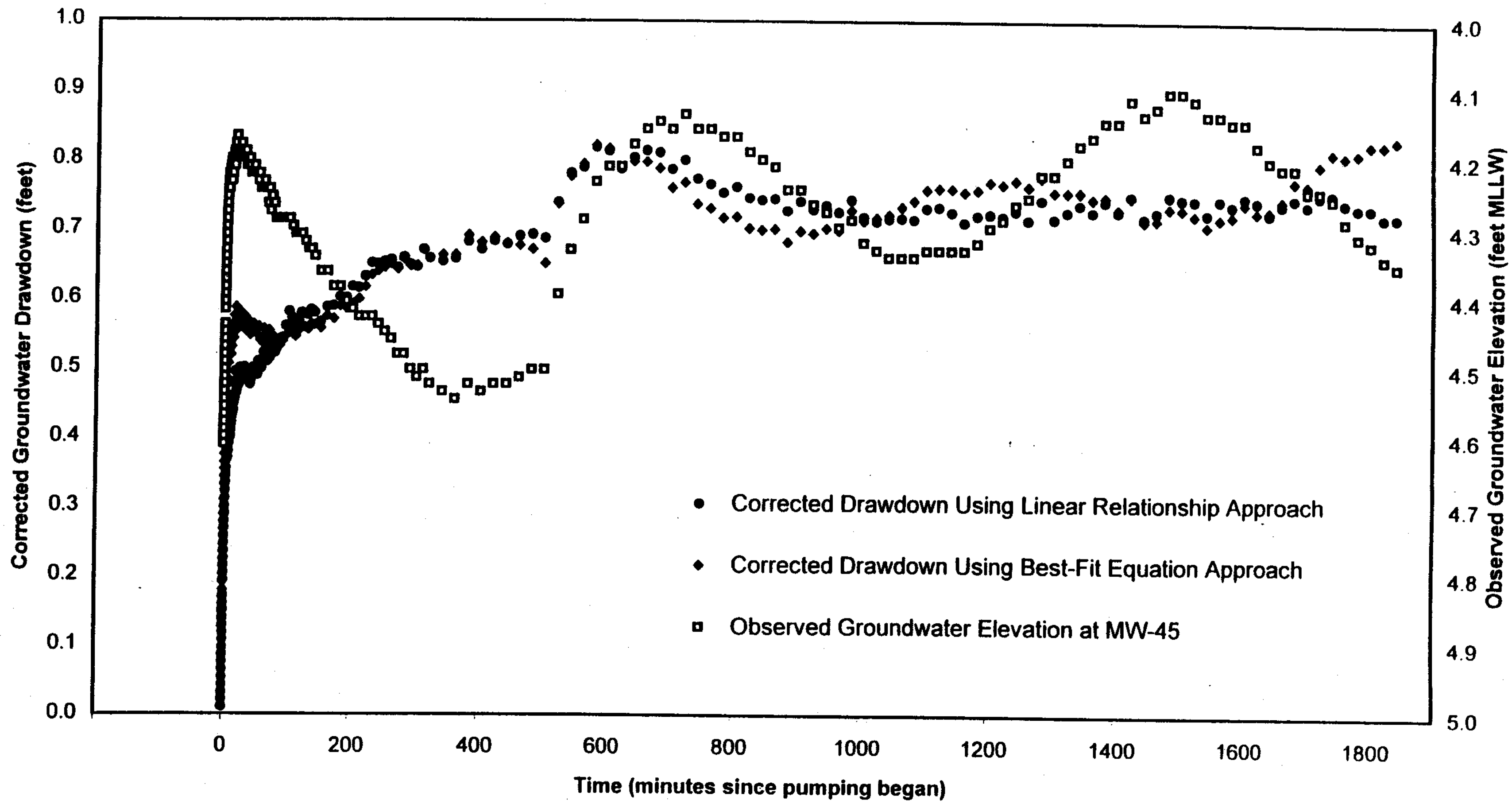

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FIGURE 5-12
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW45
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

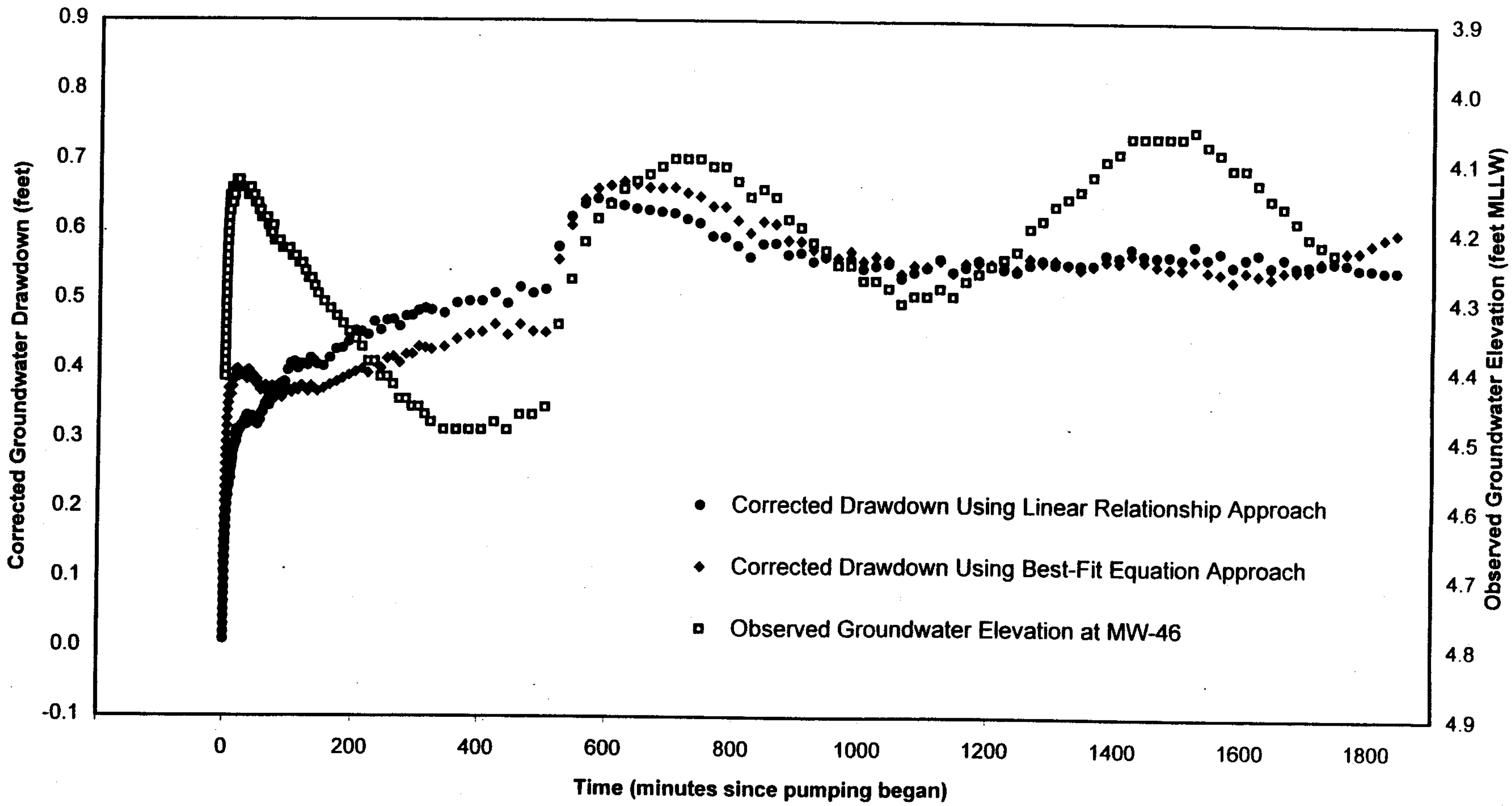

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FIGURE 5-13
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW46
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

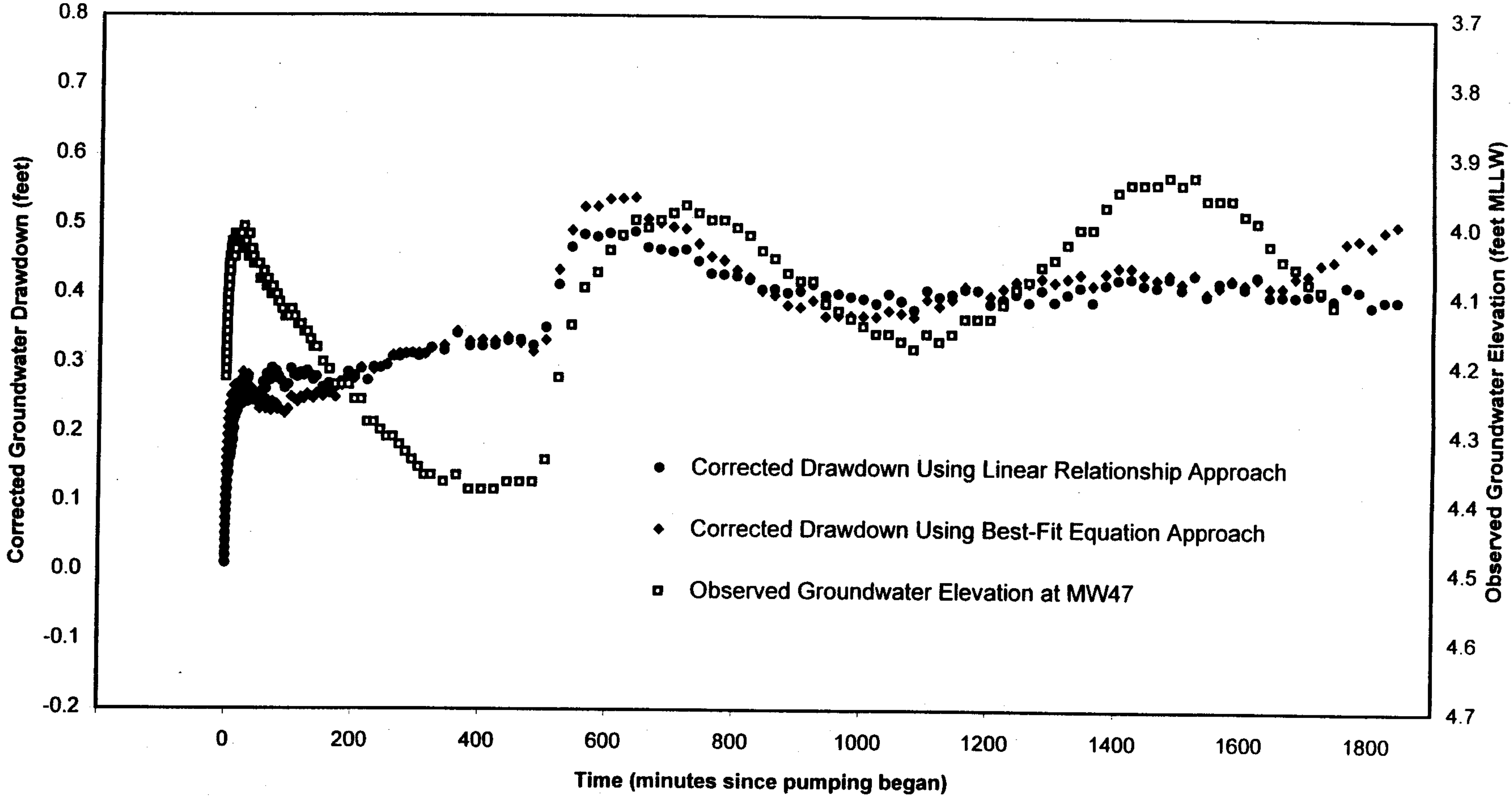

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FIGURE 5-14
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW47
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

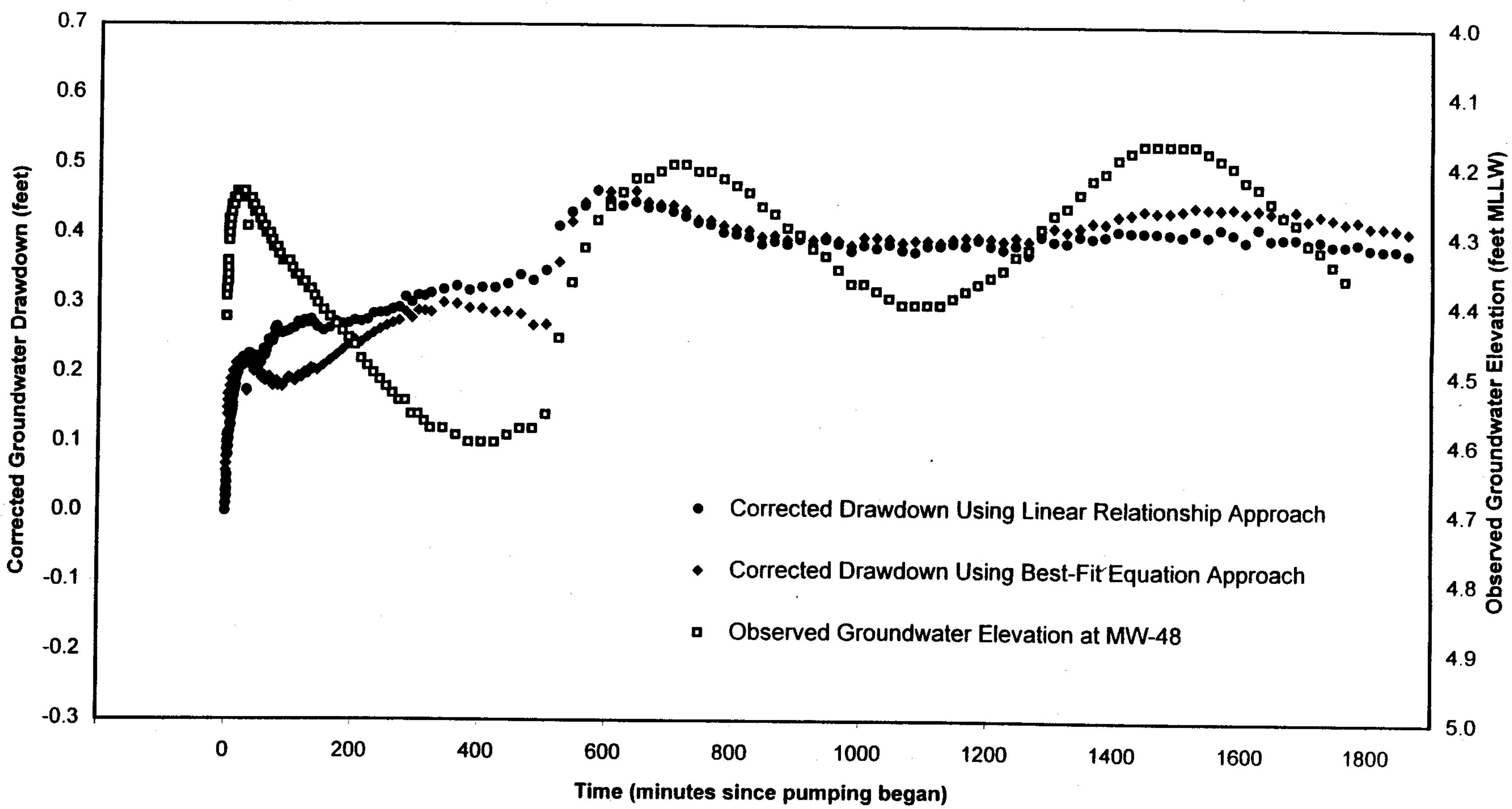

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FIGURE 5-15
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW48
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

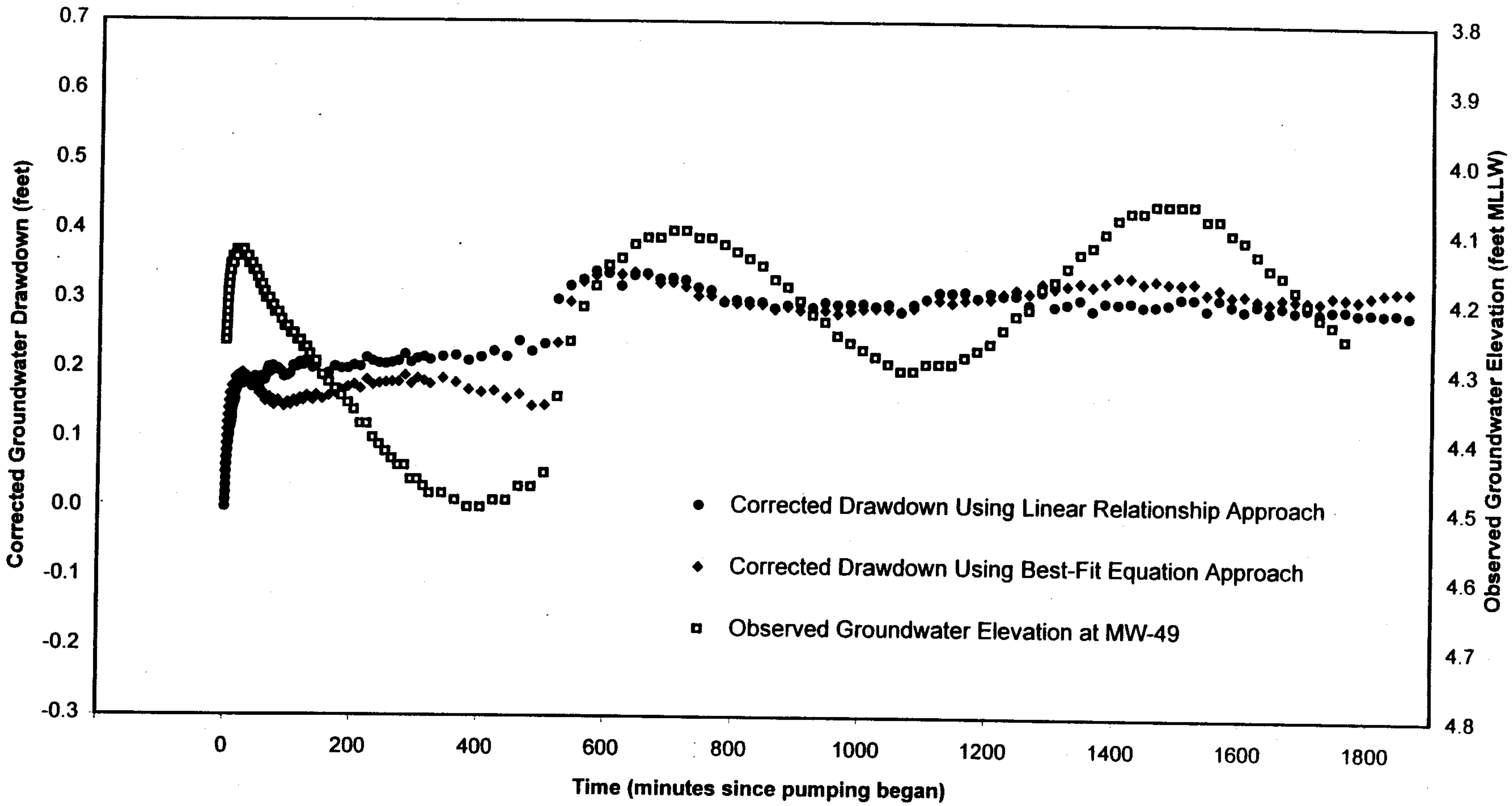

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FIGURE 5-16
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW49
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

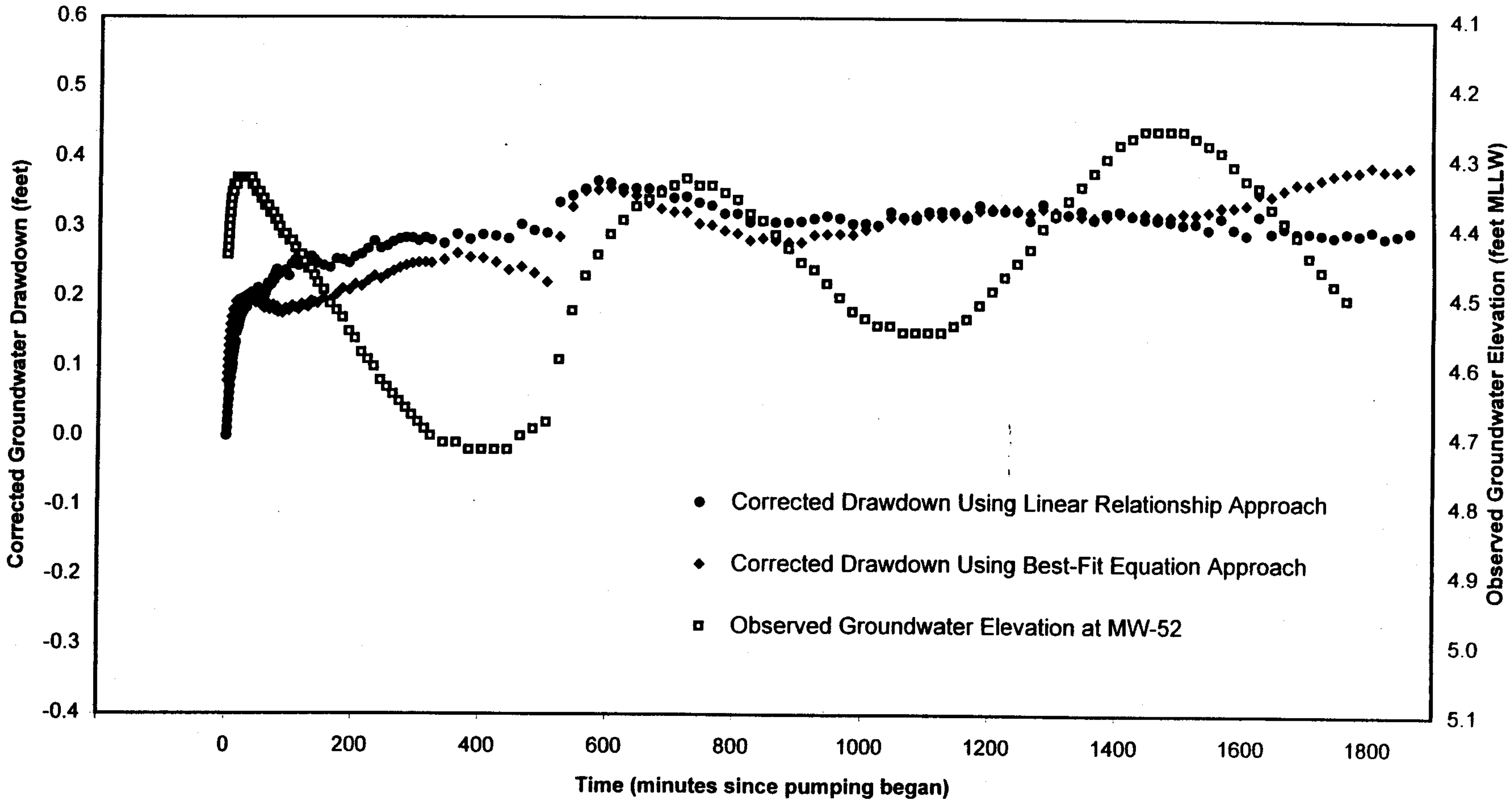

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FIGURE 5-17
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW52
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

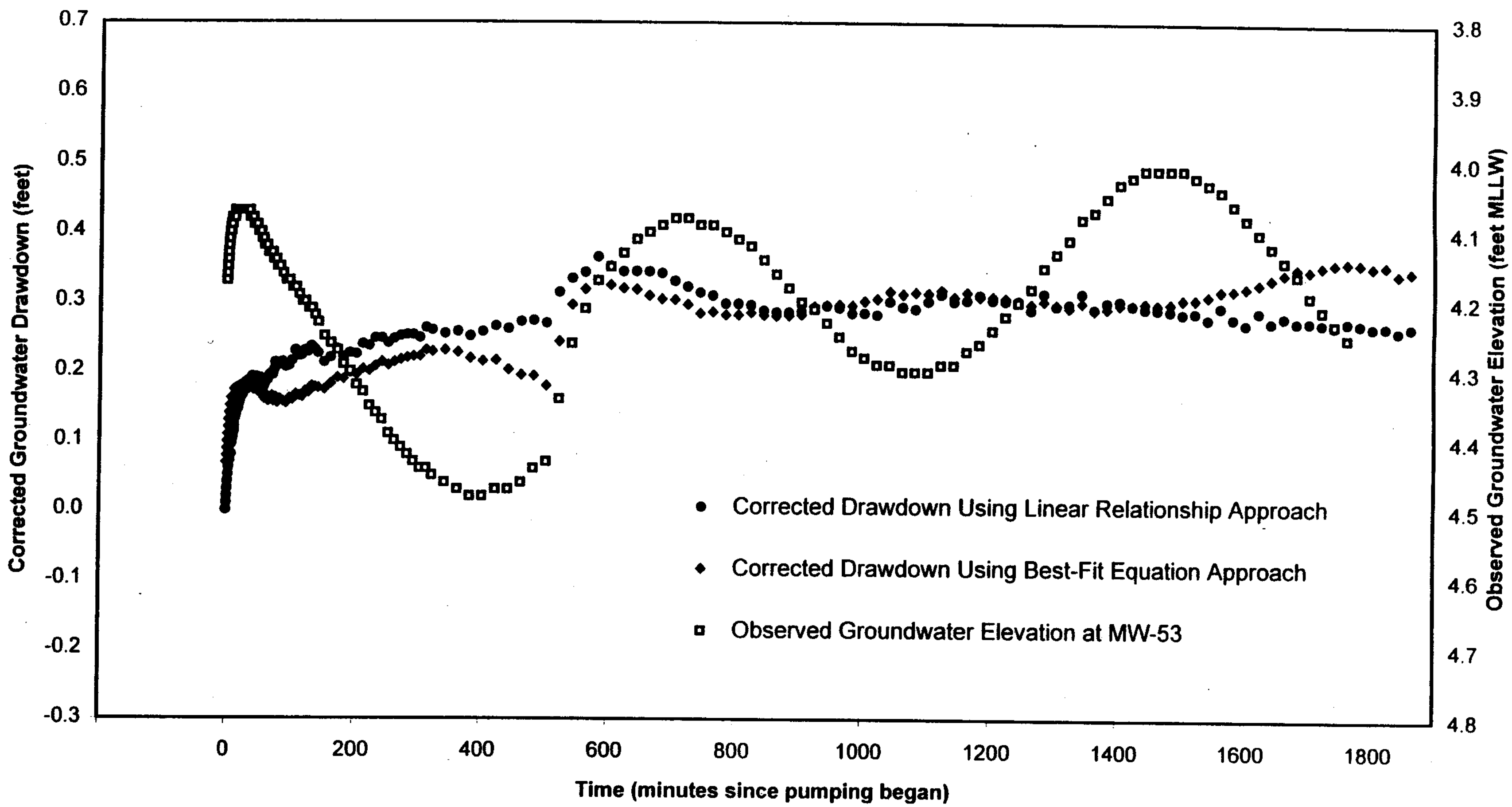

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FIGURE 5-18
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW53
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

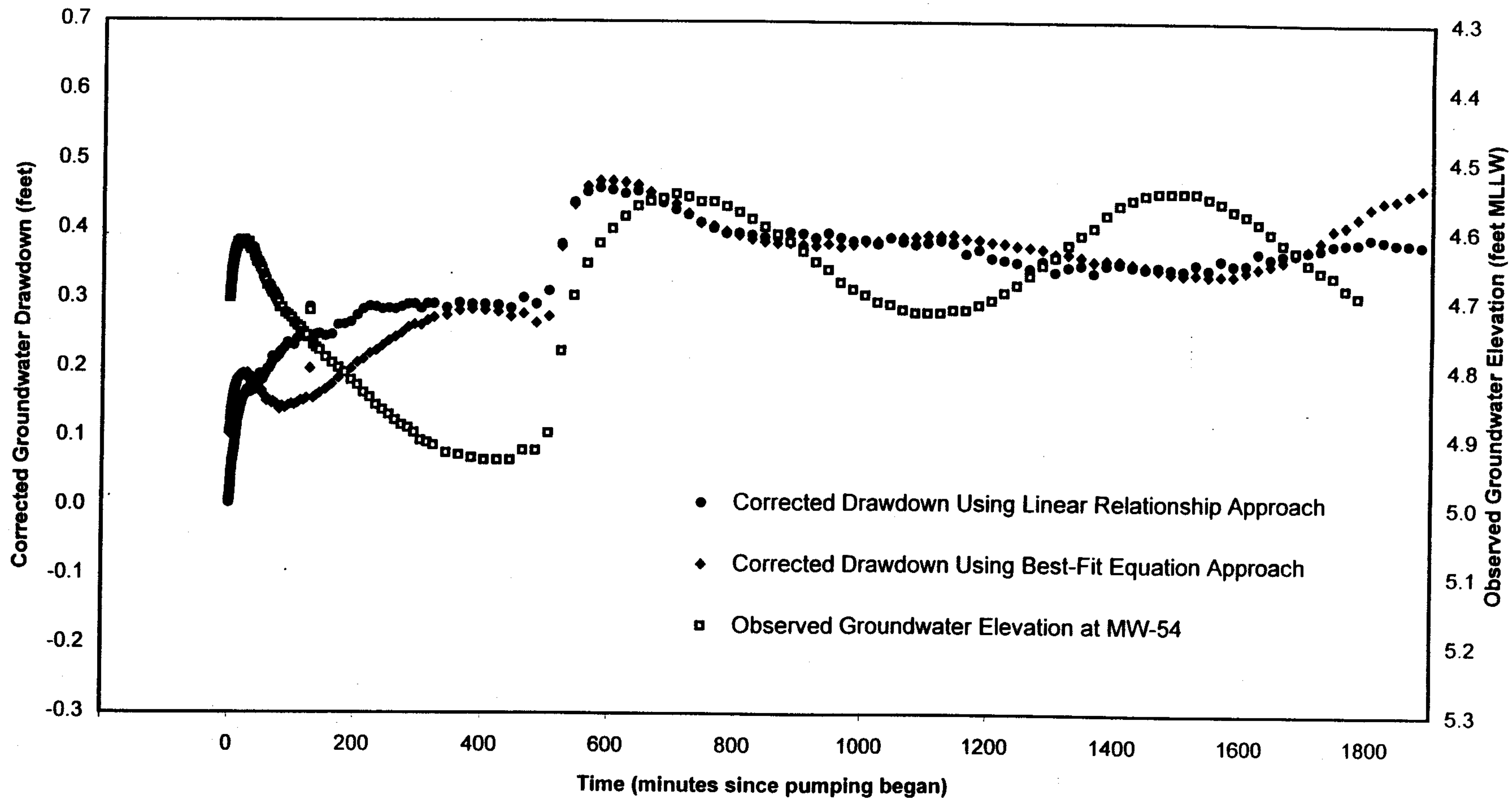

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FIGURE 5-19
OBSERVED AND CORRECTED GROUNDWATER DRAWDOWN AT WELL MW54
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.

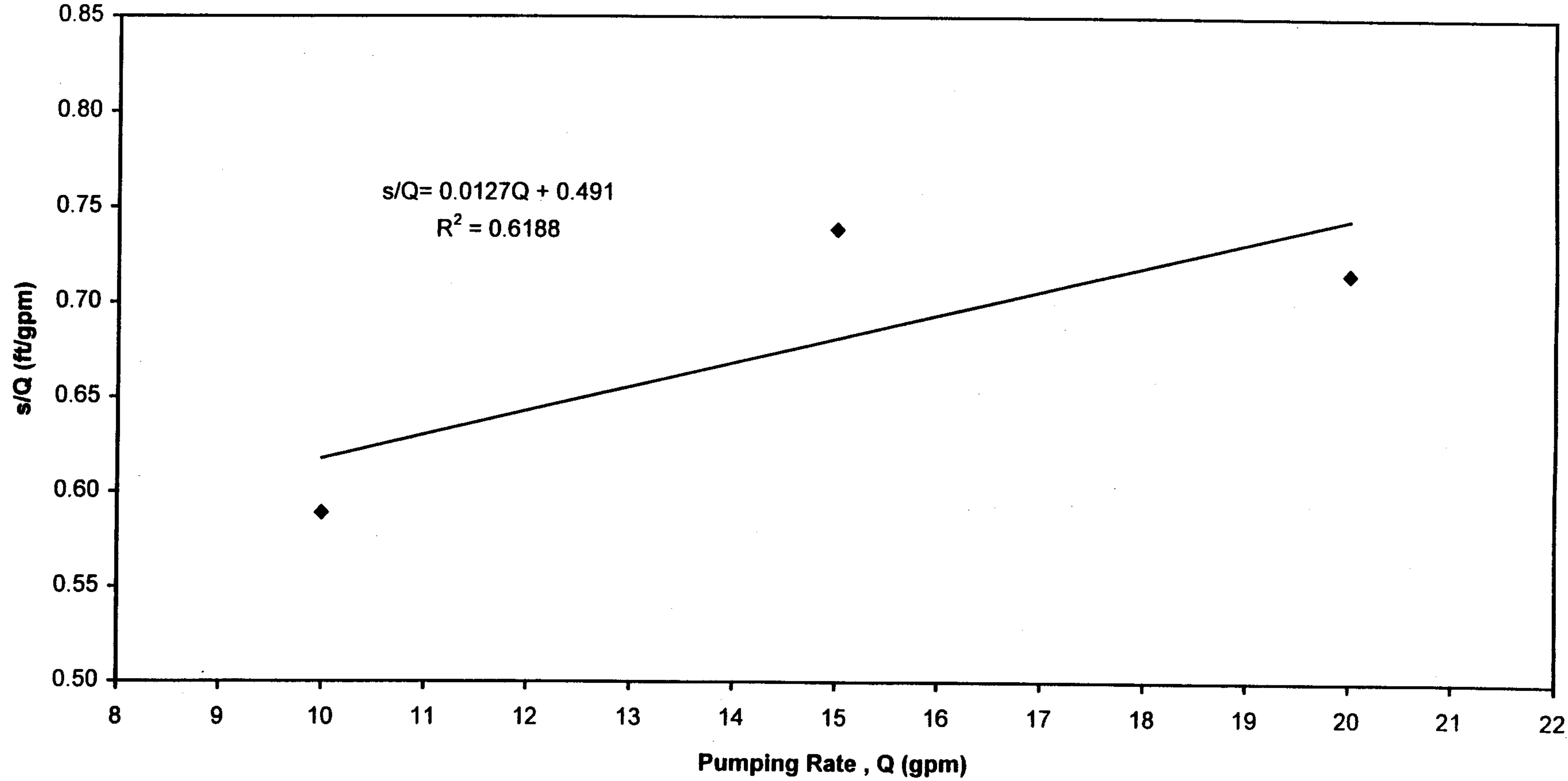

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FIGURE 5-20
s/Q vs.Q PLOTS

(Upper Aquifer Zone Step-drawdown Test)

Tetra Tech EM Inc.

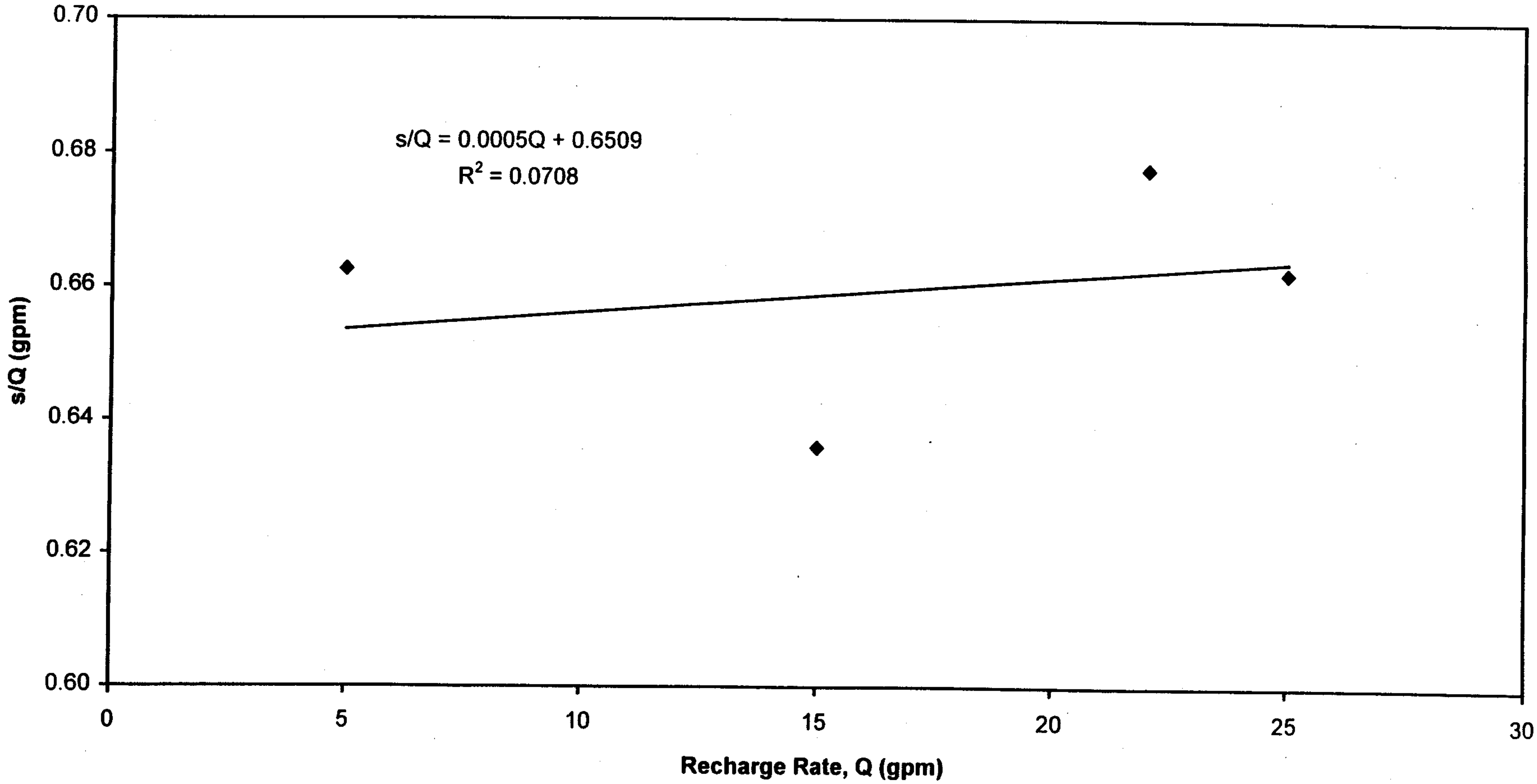

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FIGURE 5-21
s/Q vs.Q PLOTS

(Upper Aquifer Zone Injection Test)

Tetra Tech EM Inc.

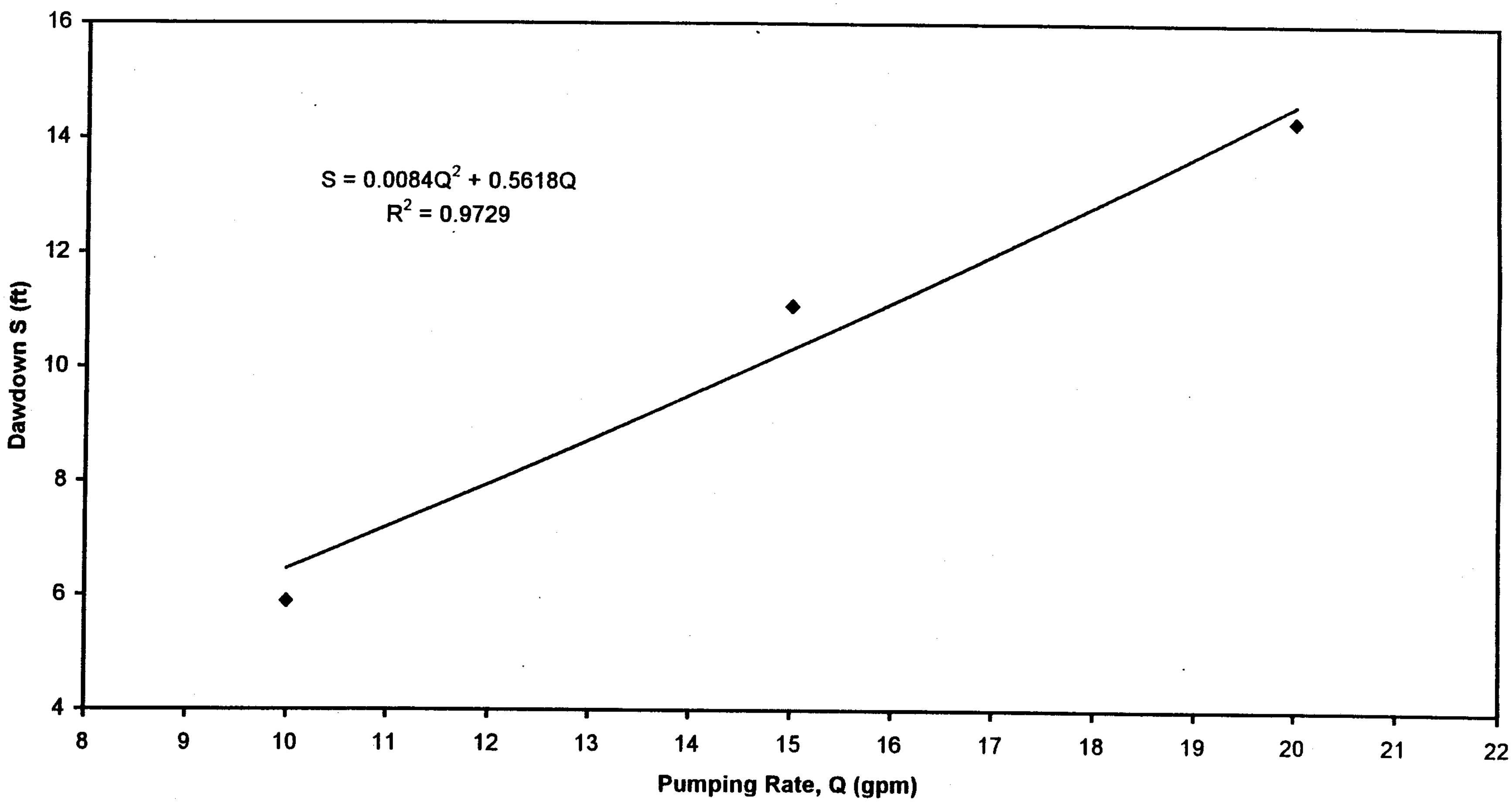

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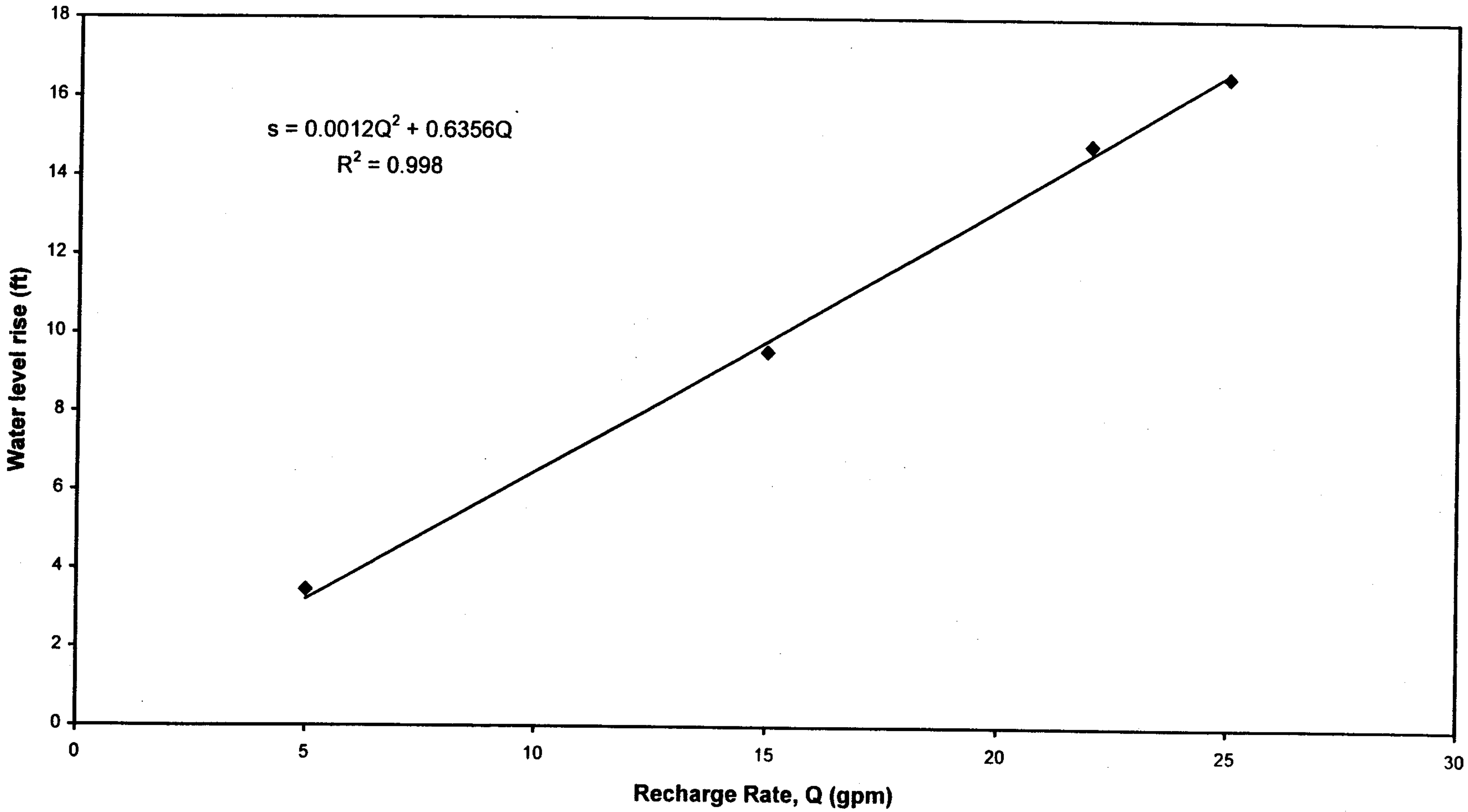
FIGURE 5-22
MAXIMUM DRAWDOWN vs.PUMPING RATE AND THE BEST FIT EQUATION
(Upper Aquifer Zone Step-drawdown Test)

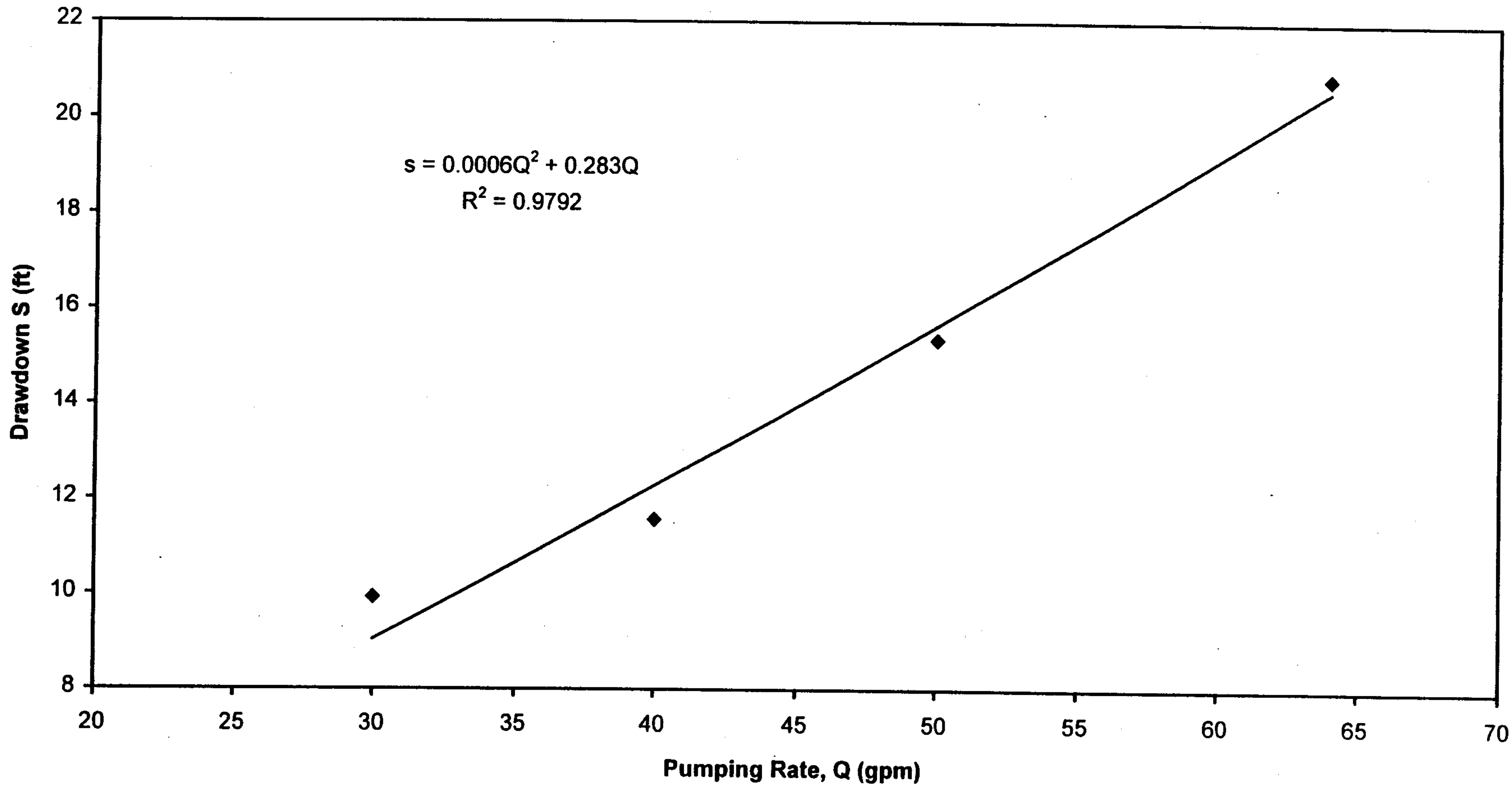
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-23
MAXIMUM WATER LEVEL RISE vs. RECHARGE RATE AND THE BEST FIT EQUATION
(Upper Aquifer Zone InjectionTest)

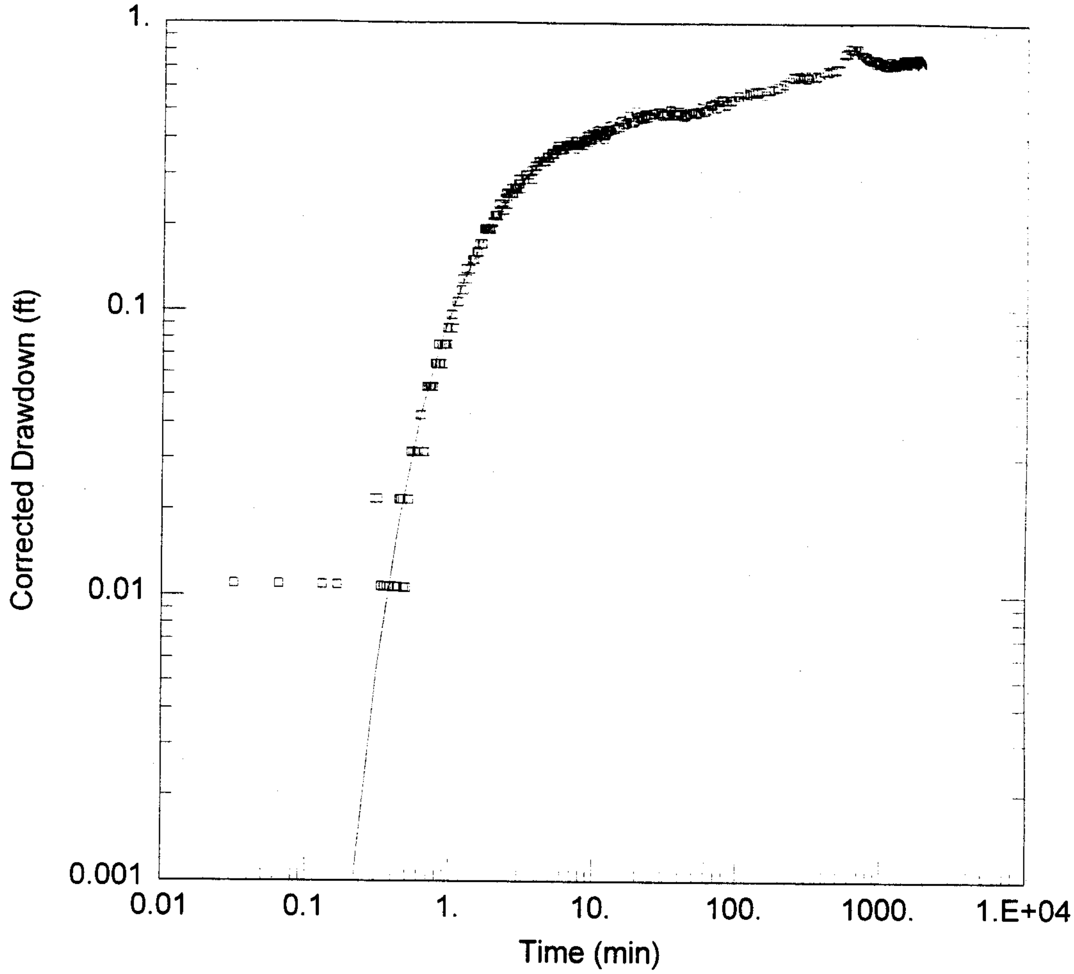
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-24
MAXIMUM DRAWDOWN vs. PUMPING RATE AND THE BEST FIT EQUATION
(Lower Aquifer Zone Step-drawdown Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW45

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW45-88.AQT
Date: 02/12/99 Time: 17:47:28

SOLUTION

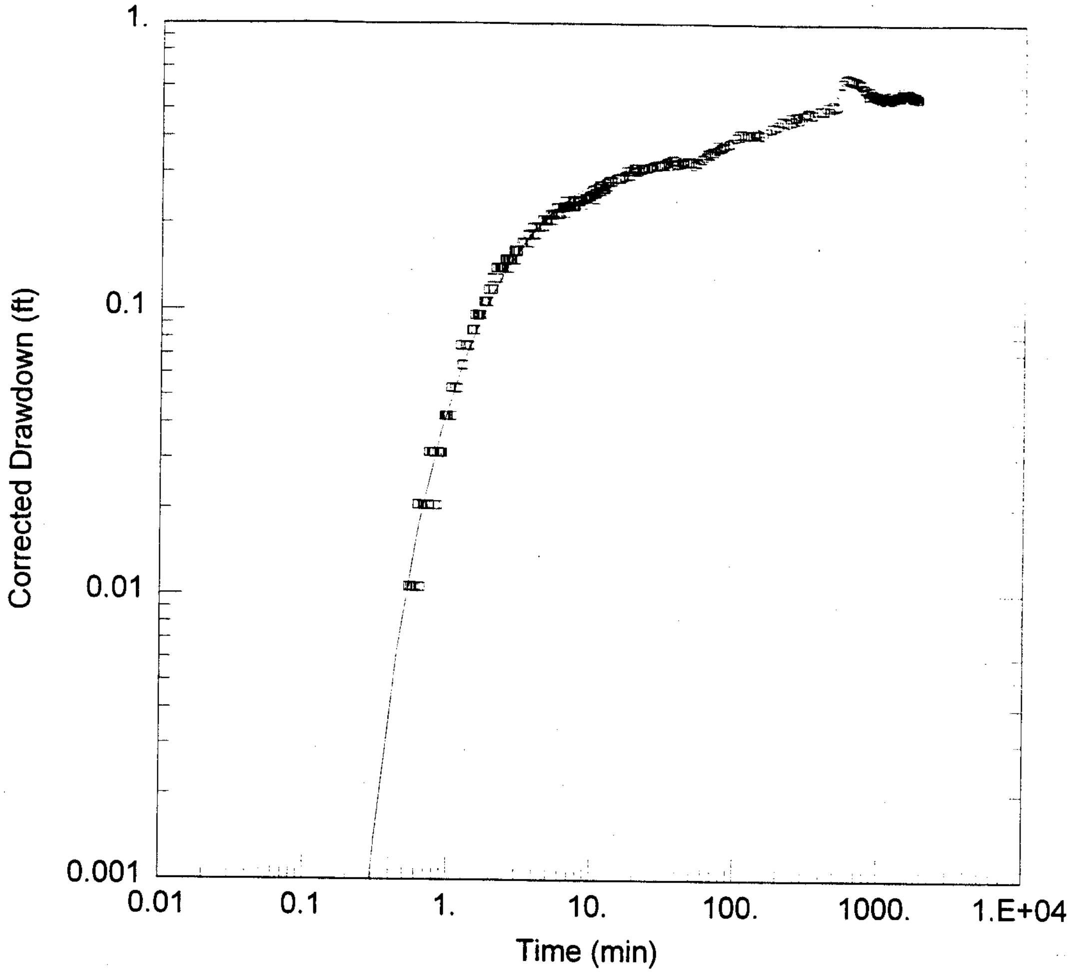
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2450. ft^2/day
S = 0.008428
Sy = 0.1201
ß = 0.03

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-25
MW45 DRAWDOWN DATA PLOT
AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW46

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW46-88.AQT
Date: 02/12/99 Time: 17:25:35

SOLUTION

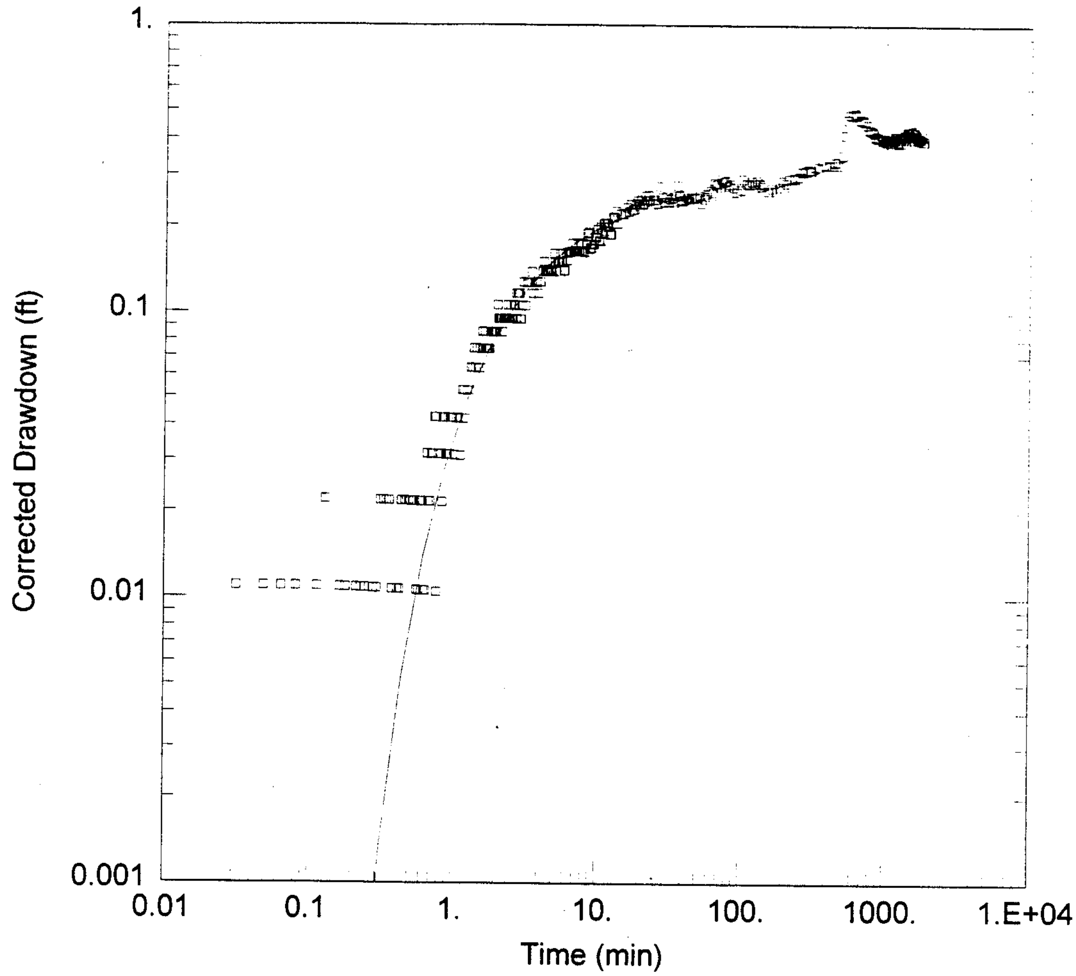
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2722.3 ft^2/day
S = 0.007299
Sy = 0.05222
ß = 0.03

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-26
MW46 DRAWDOWN DATA PLOT
AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW-47

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW47-88.AQT
Date: 02/12/99 Time: 17:25:47

SOLUTION

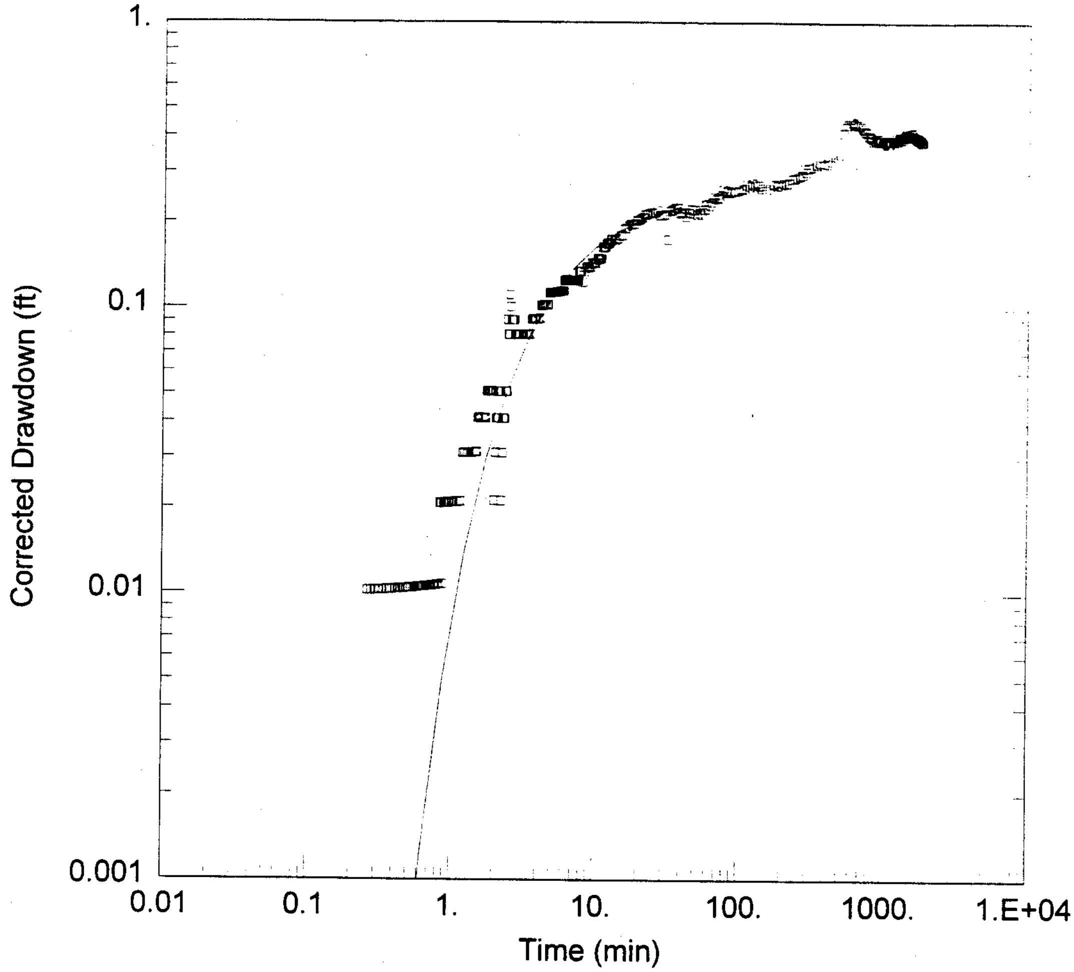
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2441.4 ft^2/day
S = 0.001919
Sy = 0.05972
ß = 0.03

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-27
MW47 DRAWDOWN DATA PLOT
AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW48

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW48-88.AQT
Date: 02/12/99 Time: 17:25:57

SOLUTION

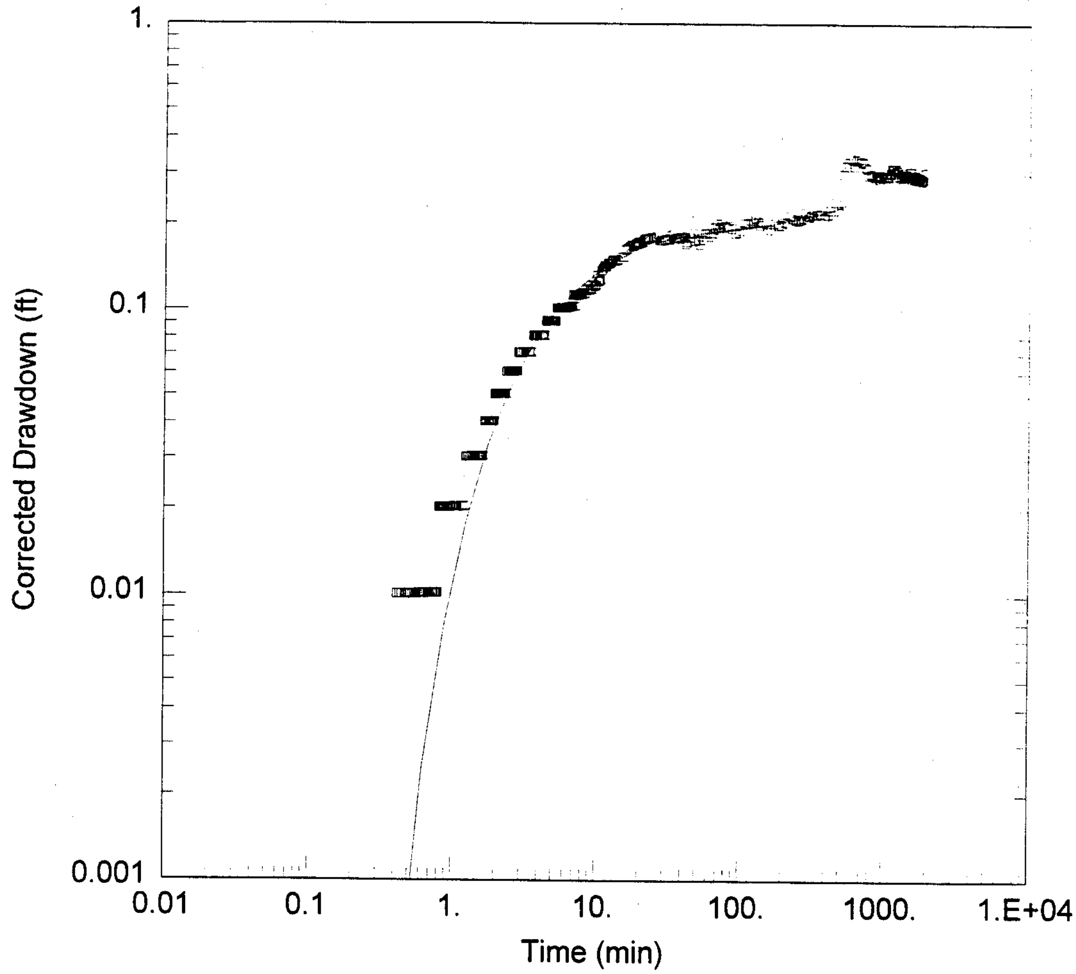
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2553. ft^2/day
S = 0.004492
Sy = 0.08931
ß = 0.09

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-28
MW48 DRAWDOWN DATA PLOT
AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW49

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW49-88.AQT
Date: 02/12/99 Time: 17:26:08

SOLUTION

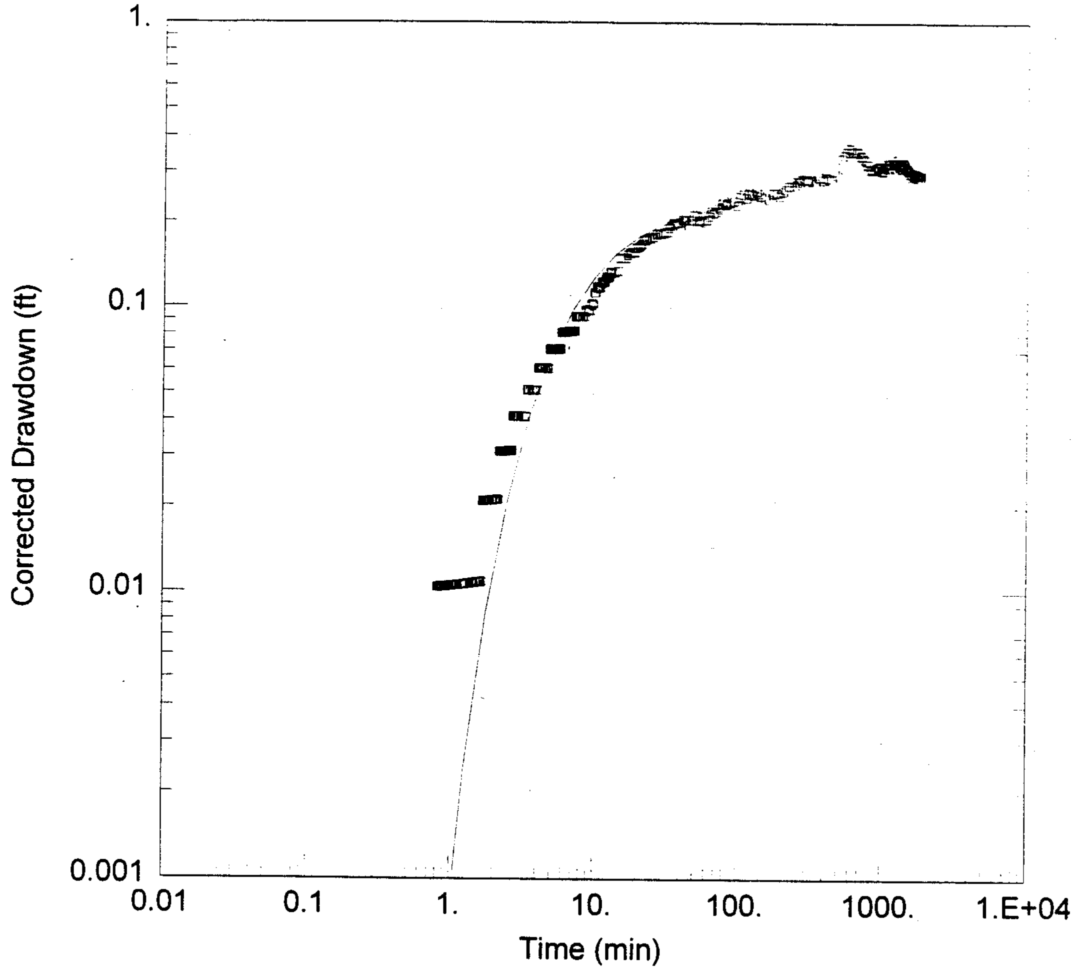
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2774. ft^2/day
S = 0.002236
Sy = 0.1075
ß = 0.08

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-29
MW49 DRAWDOWN DATA PLOT
AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW52

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW52-88.AQT
Date: 02/12/99 Time: 17:26:23

SOLUTION

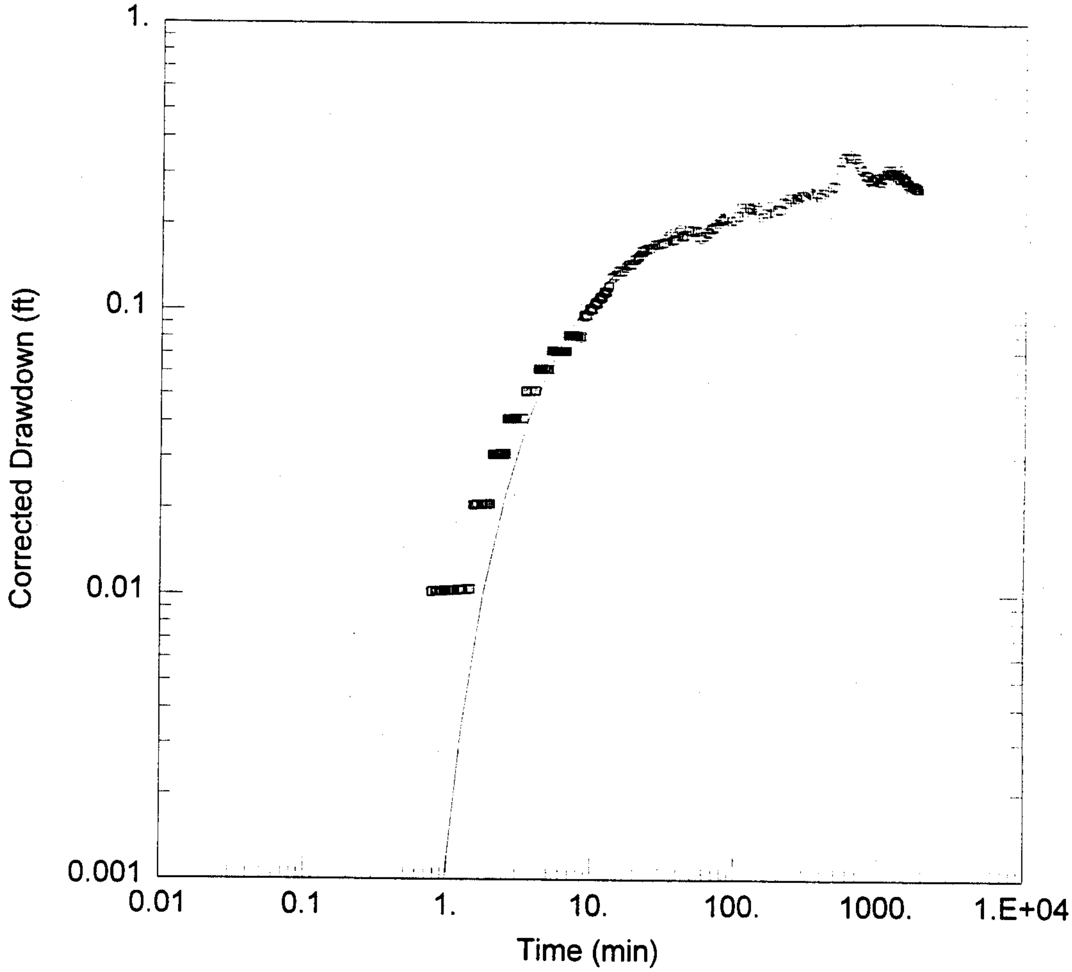
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2550. ft^2/day
S = 0.003845
Sy = 0.1
ß = 0.09

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-30
MW52 DRAWDOWN DATA PLOT
AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW53

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW53-88.AQT
Date: 02/12/99 Time: 17:26:32

SOLUTION

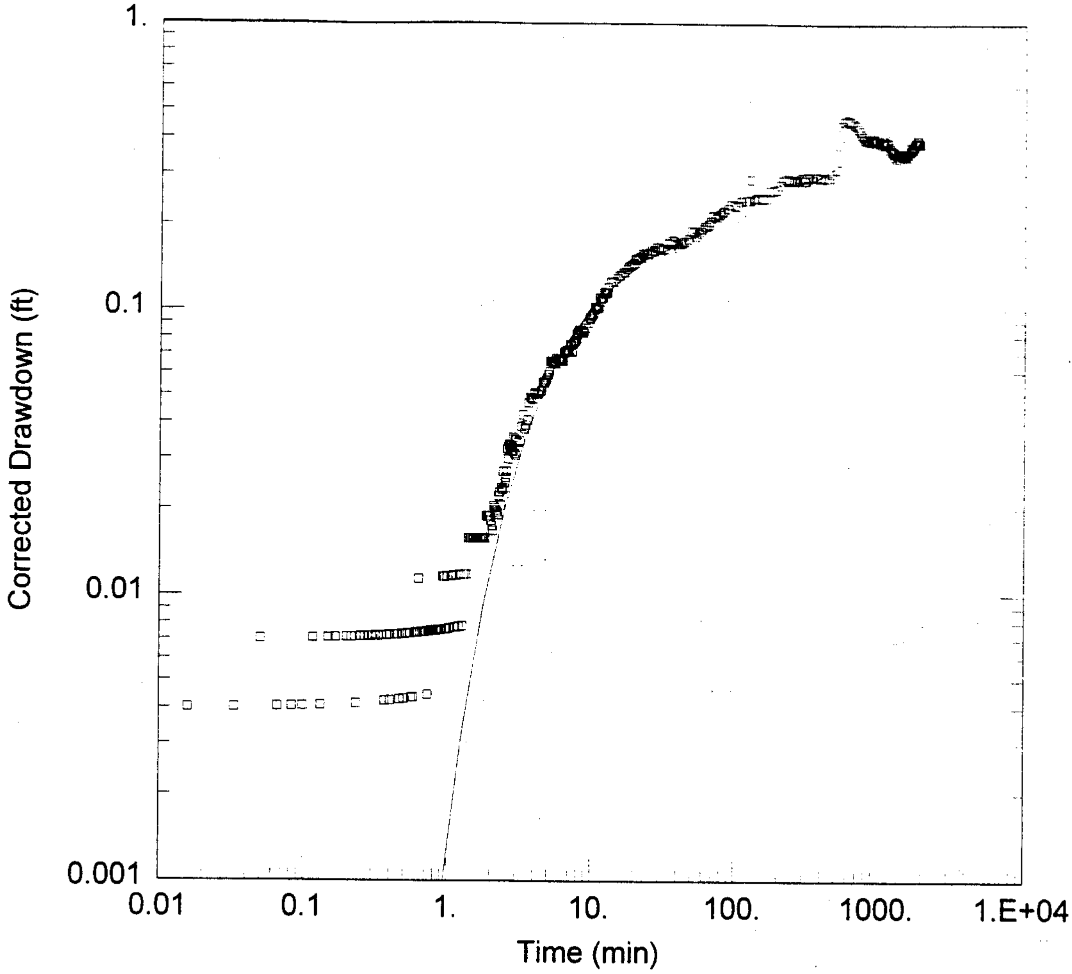
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2198.7 ft^2/day
S = 0.001353
Sy = 0.04903
ß = 0.1

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-31
MW53 DRAWDOWN DATA PLOT
AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



NAS NI SITE 9 PUMPING TEST DATA - MW54

Data Set: S:\NOVOCS\WORKIN~2\CONSTA~2\MW54-88.AQT
Date: 02/12/99 Time: 17:26:44

SOLUTION

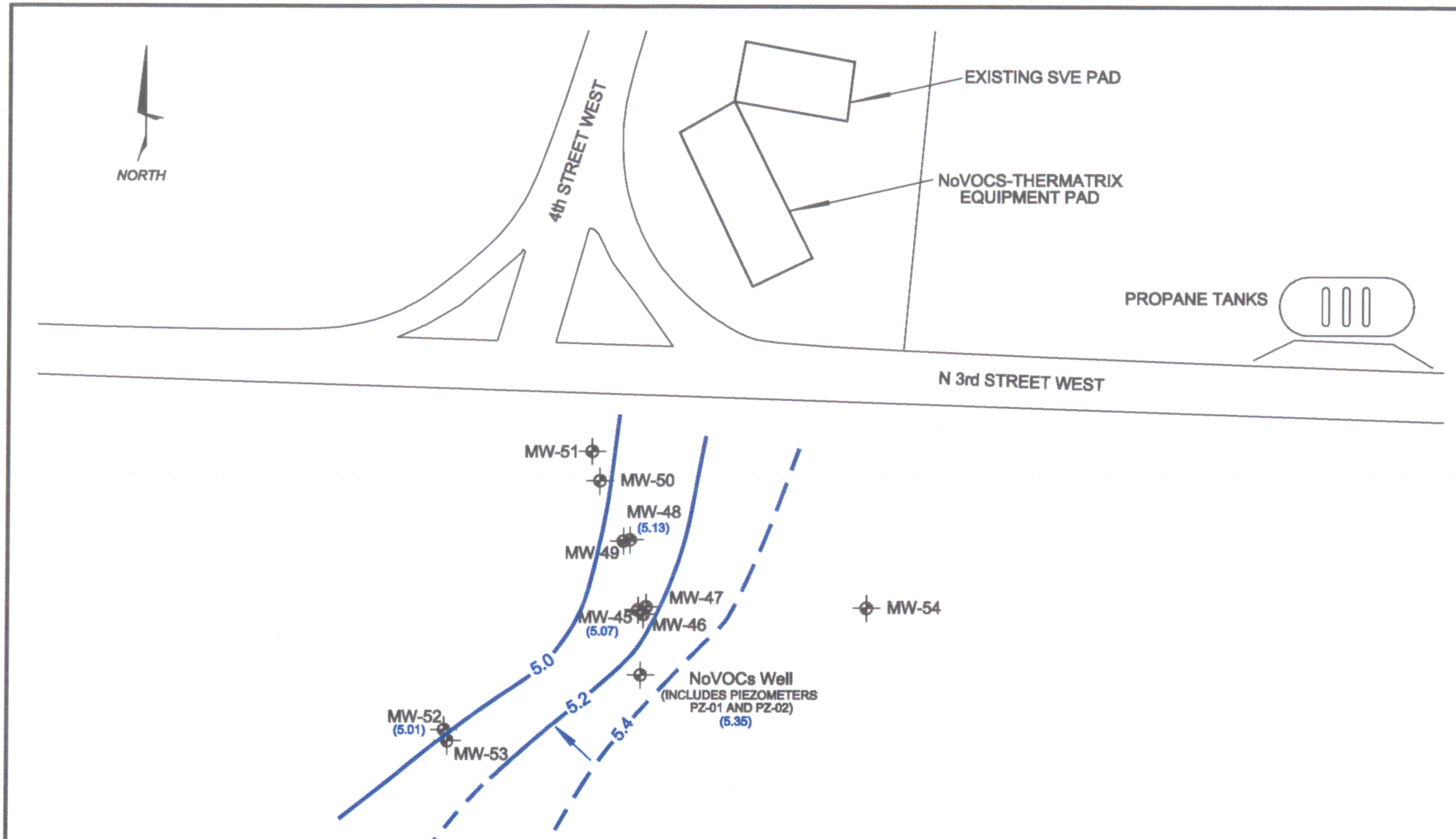
Aquifer Model: Unconfined
Solution Method: Neuman

T = 2515. ft^2/day
S = 0.002144
Sy = 0.015
ß = 0.12

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-32
MW54 DRAWDOWN DATA PLOT AND TYPE CURVE MATCH
(Upper Aquifer Zone Constant Rate Pumping Test)

Tetra Tech EM Inc.



LEGEND

MW-52 (5.01) — MONITORING WELL OR NoVOCs WELL (Equivalent Fresh Water Head Elevation in Feet)

—5.0— THE MEAN EQUIVALENT FRESH WATER HEAD ELEVATION (MLLW) CONTOUR LINE WITH CONTOUR INTERVAL IN FEET

MEAN GROUND WATER FLOW DIRECTION

0 50 100

SCALE IN FEET

NAS NORTH ISLAND SITE 9

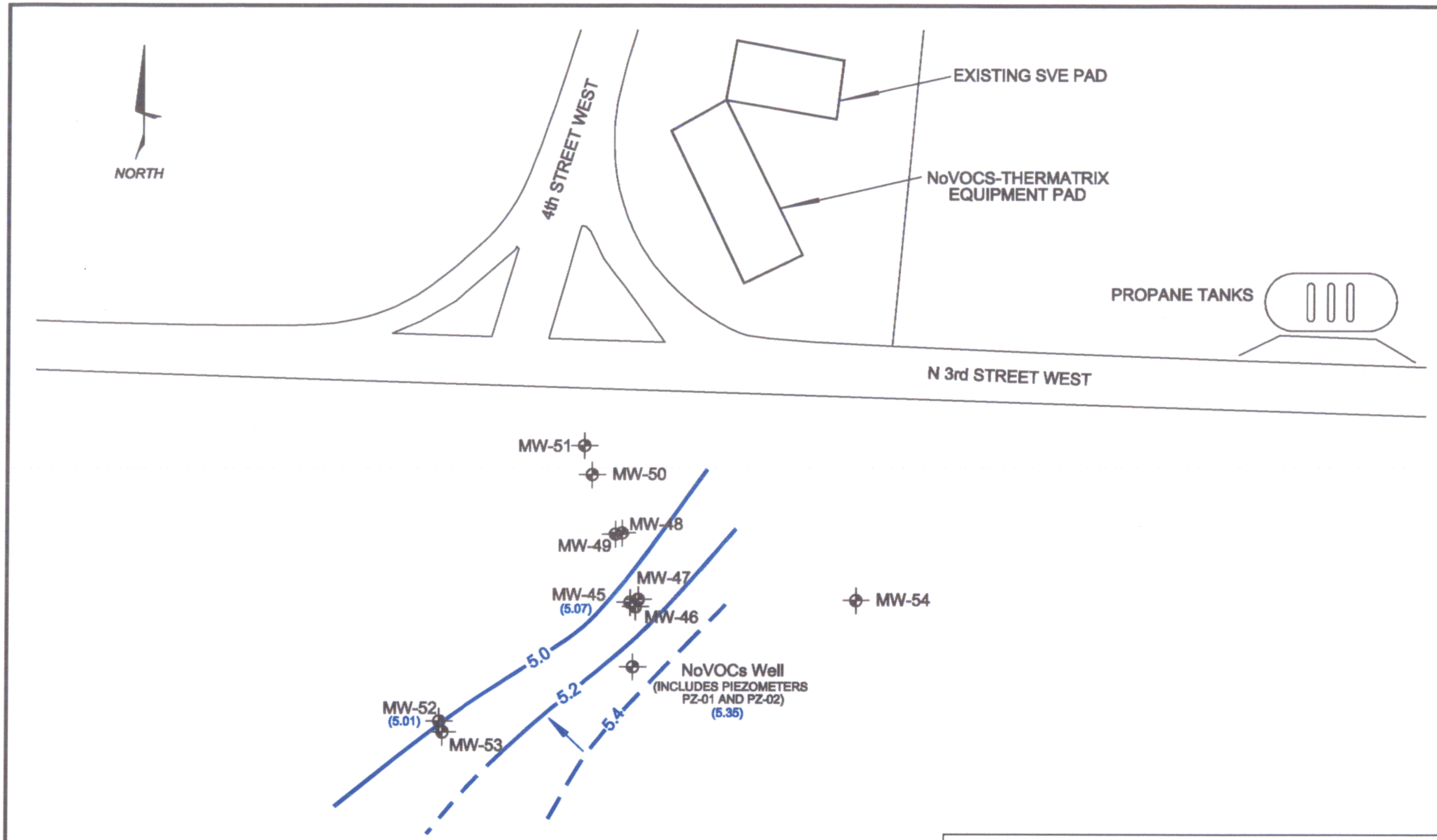
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-33

THE MEAN EQUIVALENT FRESH-WATER HEAD CONTOUR AND HORIZONTAL GROUNDWATER FLOW DIRECTION

(Upper Aquifer Zone, Four Data Points, August 1998)

Tetra Tech EM Inc.



LEGEND

MW-52 (5.01) MONITORING WELL OR NoVOCs WELL (Equivalent Fresh Water Head Elevation in Feet)

5.0 THE MEAN EQUIVALENT FRESH WATER HEAD ELEVATION (MLLW) CONTOUR LINE WITH CONTOUR INTERVAL IN FEET

MEAN GROUND WATER FLOW DIRECTION

0 50 100

SCALE IN FEET

NAS NORTH ISLAND SITE 9

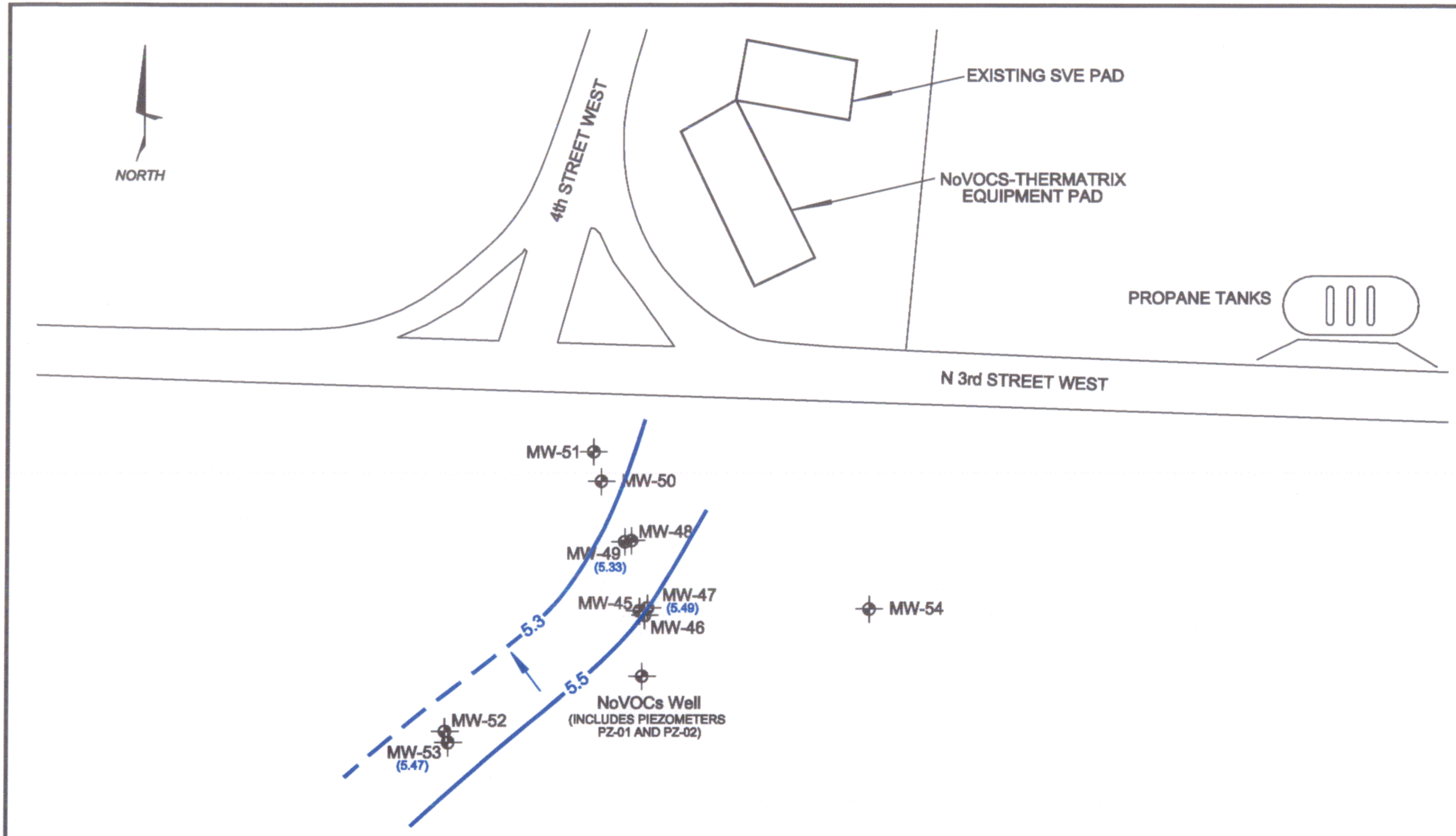
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-34

THE MEAN EQUIVALENT FRESH-WATER HEAD CONTOUR AND HORIZONTAL GROUNDWATER FLOW DIRECTION

(Upper Aquifer Zone, Three Data Points, August 1998)

Tetra Tech EM Inc.



LEGEND

MW-53 (5.47) — MONITORING WELL OR NoVOCs WELL (Equivalent Fresh Water Head Elevation in Feet)

5.3 — THE MEAN EQUIVALENT FRESH WATER HEAD ELEVATION (MLLW) CONTOUR LINE WITH CONTOUR INTERVAL IN FEET

MEAN GROUND WATER FLOW DIRECTION

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 5-35

THE MEAN EQUIVALENT FRESH-WATER HEAD CONTOUR AND HORIZONTAL GROUNDWATER FLOW DIRECTION
(Lower Aquifer Zone, Three Data Points, August 1998)

Tetra Tech EM Inc.

TABLE 5-1

TIDAL INFLUENCE PARAMETER VALUES
TIDAL INFLUENCE STUDY OF APRIL 10 THROUGH 20, 1998
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Measurement Point	Range (feet)			Tidal Efficiency			Time Lag (minutes)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
San Diego Bay	1.72	8.11	5.27	1.00	1.00	1.00	0	0	0
MW45	0.11	0.58	0.36	0.05	0.08	0.07	52	94	70
MW46	0.09	0.56	0.36	0.05	0.08	0.07	52	94	71
MW47	0.09	0.58	0.36	0.05	0.08	0.07	46	94	72
MW48	0.10	0.58	0.36	0.05	0.08	0.07	52	90	72
MW49	0.11	0.58	0.37	0.05	0.08	0.07	56	93	71
MW50	0.10	0.60	0.37	0.05	0.08	0.07	52	96	72
MW52	0.12	0.72	0.46	0.07	0.10	0.09	46	85	69
MW53	0.12	0.73	0.45	0.06	0.10	0.09	54	93	70

Note:

Values presented are based on calculations for each of the 39 tidal periods during the 10-day study. A tidal period extends from consecutive high to low or low to high tidally influenced groundwater levels.

TABLE 5-2

PARAMETERS USED IN TIDAL CORRECTION FOR THE CONSTANT DISCHARGE PUMPING TEST NoVOCs™ HYDROGEOLOGICAL INVESTIGATION NAS NORTH ISLAND

Well ID	Tidal Efficiency			Time Lag (minutes)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
MW45	0.05	0.10	0.09	52	94	73
MW46	0.05	0.10	0.09	52	94	72
MW47	0.05	0.10	0.09	50	94	72
MW48	0.05	0.10	0.08	52	93	71
MW49	0.05	0.10	0.08	52	93	70
MW52	0.07	0.11	0.10	50	90	70
MW53	0.06	0.11	0.10	50	90	70
MW54	0.05	0.09	0.07	52	94	72

TABLE 5-3

AQUIFER TEST DATA AND THE NoVOCs™ WELL SPECIFIC CAPACITY
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Type of Test	Test Step	Pumping or Recharge Rate (Q) (gpm)	Measured Maximum Drawdown or Water Level Rise(s) (feet)	Specific Capacity[a] (gpm/foot)	Average Specific Capacity (gpm/ft)
Upper Aquifer zone Step Drawdown Test	1	10	5.89	1.70	1.48
	2	15	11.08	1.35	
	3	20	14.31	1.40	
Upper Aquifer zone Injection Test	1	5	3.45	1.45	1.50
	2	15	9.54	1.57	
	3	22	14.82	1.48	
	4	25	16.56	1.51	
Deep Aquifer zone Step Drawdown Rest	1	40	11.40	3.51	3.22
	2	50	15.35	3.26	
	3	64	20.86	3.07	
	4	30	9.92	3.02	

Notes:

a Specific capacity was calculated by dividing pumping or recharge rate (Q) by maximum drawdown or water level rise (s).

gpm gallons per minute

TABLE 5-4

AQUIFER TEST DATA AND WELL EFFICIENCY
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Type of Test	Pumping or Recharge Rate (Q) (gpm)	Measured Maximum Drawdown or Water Level Rise (s) (feet)	Well Loss Coefficient[a] (C)	Well Loss[a] (CQ^2) (feet)	Well Efficiency[b] (%)	Average Well Efficiency (%)
Upper Aquifer zone Step Drawdown Test	10	5.89	0.0084[c]	0.84	85	82
	15	11.08		1.89	83	
	20	14.31		3.36	77	
Upper Aquifer zone Injection Test	5	3.45	0.0012[d]	0.03	99	97
	15	9.54		0.27	97	
	22	14.82		0.58	96	
	25	16.56		0.75	95	
Deep Aquifer zone Step Drawdown Test	30	9.92	0.0006[e]	0.54	95	91
	40	11.57		0.96	92	
	50	15.35		1.50	90	
	64	20.86		2.46	88	

Notes:

a Defined by Equation 5-18

b Calculated using Equation 5-19, where well efficiency in percent (E_{well}) is defined as follows: $E_{well} = \frac{s - CQ^2}{s} \times 100$

c From best fit equation for data in Figure 5-11
d From best fit equation for data in Figure 5-12
e From best fit equation for data in Figure 5-13
gpm gallons per minute

TABLE 5-5

UPPER AQUIFER ZONE
CONSTANT DISCHARGE PUMPING TEST CONFIGURATION
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

GENERAL INFORMATION	
Pumping well:	NoVOCs™ well (upper screen interval)
Pumping well casing diameter:	8 inches
Pumping rate:	20 gallons per minute
Pumping duration:	32 hours
Initial groundwater level:	17 feet bgs
Aquifer saturation thickness:	88 feet

PUMPING AND OBSERVATION WELL INFORMATION

Well ID[a]	Distance from the Pumping Well (feet)	Screen Interval	
		Depth (feet bgs)	Elevation (feet relative to MLLW)
IW-01 (NoVOCs™ well)	0	43 to 47 and 72 to 78	-21.3 to -25.3 and -50.3 to -56.3
MW-45	29.8	42 to 47	-20.0 to -25.0
MW-46	27.7	57 to 62	-35.4 to -40.4
MW-47	31.1	72 to 78	-49.9 to -55.9
MW-48	61.9	52 to 57	-28.6 to -33.6
MW-49	61.7	67 to 72	-43.6 to -48.6
MW-52	93.0	41 to 46	-19.1 to -24.1
MW-53	93.1	72 to 77	-50.4 to -55.4
MW-54	107.9	38 to 78	-18.0 to -58.0

Notes:

a Observation wells MW-50 and MW-51 are not included because no data are available due to datalogger malfunction

bgs Below ground surface

MLLW Mean lower low water level

TABLE 5-6

CONSTANT DISCHARGE PUMPING TEST INFORMATION
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Well ID	Well Function	Distance from Pumping Well (feet)	Initial Response Time (minute)	Maximum Drawdown at the End of the Test[a] (feet)	Screen Interval	
					Depth (feet bgs)	Elevation (feet relative to MLLW)
NoVOCs™ Well (upper screen)	Pumping	0	0	16.02	43 to 47	-21.3 to -25.3
MW-45	Observation	29.8	0.51	0.63	42 to 47	-20.0 to -25.0
MW-46	Observation	27.7	0.53	0.46	57 to 62	-35.4 to -40.4
MW-47	Observation	31.1	0.66	0.40	72 to 78	-49.9 to -55.9
MW-48	Observation	61.9	0.75	0.23	52 to 57	-28.6 to -33.6
MW-49	Observation	61.7	0.75	0.18	67 to 72	-43.6 to -48.6
MW-52	Observation	93.0	0.80	0.22	41 to 46	-19.1 to -24.1
MW-53	Observation	93.1	0.90	0.20	72 to 77	-50.4 to -55.4
MW-54	Observation	107.9	1.30	0.26	38 to 78	-18.0 to -58.0

Notes:

a Observation well drawdown data have been tidally corrected
bgs Below ground surface
MLLW Mean lower low water level

TABLE 5-7

AQUIFER HYDRAULIC PARAMETERS
UPPER AQUIFER CONSTANT DISCHARGE PUMPING TEST
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Observation Well	Transmissivity (T) ($feet^2$/day)	Hydraulic Conductivity (K)		Storativity (S) (dimensionless)	Specific Yield (S_y) (dimensionless)	Neuman Delayed Yield factor (β) (dimensionless)	Ratio of Vertical to Horizontal K (K_Z/K_r) (dimensionless)
		(feet/day)	(cm/sec)				
MW-45	2,450	28	0.010	0.0084	0.12	0.03	0.26
MW-46	2,722	31	0.011	0.0073	0.05	0.03	0.30
MW-47	2,441	28	0.010	0.0019	0.06	0.03	0.24
MW-48	2,553	29	0.010	0.0045	0.09	0.09	0.18
MW-49	2,774	32	0.011	0.0022	0.11	0.08	0.16
MW-52	2,550	29	0.010	0.0038	0.10	0.09	0.08
MW-53	2,199	25	0.009	0.0014	0.05	0.10	0.09
MW-54	2,515	29	0.010	0.0021	0.02	0.12	0.08
Average	2,526	29	0.010	0.0040	0.07	0.07	0.17

TABLE 5-8

MEAN GROUNDWATER AND EQUIVALENT FRESH-WATER HEADS
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Aquifer Zone	Well ID	Mean Groundwater Elevation after Tidal Correction (feet MLLW)	Parameters Used in Calculating Equivalent Fresh- Water Heads				Equivalent Fresh - Water Heads[c] (feet MLLW)
			TDS Concentration (mg/L)	Groundwater Density[a] (kg/m^3)	Groundwater Specific Gravity (unitless)	Well Screen Elevation[b] (feet MLLW)	
Upper Zone	MW45	4.78	17,600	1,011	1.011	-22.51	5.07
	MW48	4.56	25,700	1,016	1.016	-31.08	5.13
	MW52	4.64	22,700	1,014	1.014	-21.55	5.01
	PW	4.97	21,300	1,013	1.013	-23.77	5.35
Lower Zone	MW47	4.33	32,000	1,020	1.020	-52.35	5.49
	MW49	4.40	29,200	1,019	1.019	-46.08	5.33
	MW53	4.34	31,000	1,020	1.020	-52.91	5.47

Notes:

A Density is calculated based on Equation 5-31
B Well screen elevation is determined as the middle point of the well screen
C Equivalent fresh- water head is calculated based on Equation 5-30

6.0 CONCLUSIONS

The hydrogeological investigation of the aquifer treated by the NoVOCs™ system has yielded valuable information regarding the hydraulic characteristics of the aquifer, pumping and injection capacities of the NoVOCs™ well, and defects in the NoVOCs™ well. The conclusions of the investigation are as follows:

- The tested aquifer is significantly influenced by tidal fluctuations in San Diego Bay, as demonstrated by the drawdown data collected from the observation wells during the constant discharge pumping test of the NoVOCs™ well.

- The tidal effects on groundwater levels must be corrected to allow the calculation of aquifer parameters and the mean groundwater elevations.

- Groundwater levels must be corrected for density effect for determination of groundwater flow patterns. The mean equivalent fresh water head contour maps show that groundwater at the vicinity of the NoVOCs™ well flows to the west or northwest in both of the upper and lower aquifer zones. The horizontal hydraulic gradient of the two aquifer zones ranges from 0.005 to 0.01.

- Two methods were developed for tidal correction of groundwater drawdown data obtained during the constant discharge pumping test. The methods involve using the tidal influence study data collected in April 1998 to calculate the tidal efficiency and time lag for each of the observation wells. The estimated tidal efficiency ranges from 0.05 to 0.1 in different tidal cycles at different wells; the estimated time lags range from 46 to 96 minutes.

- Observed drawdown data collected during the constant discharge pumping test were corrected using the two new tidal correction methods. The corrected drawdown (that is, drawdown data with the tidal effects removed) using both methods correlates well with each other and reflects typical pumping test responses. The corrected drawdown matches reasonably well with Neuman type curves for the aquifer parameter estimation.

- The aquifer hydraulic parameters were estimated based on the tidally corrected groundwater drawdown data for the constant discharge pumping test. The average hydraulic conductivity was estimated as 29ft/day or 0.01 cm/sec. The average aquifer storativity and specific yield are 0.004 and 0.07. The average ratio of horizontal to vertical hydraulic conductivity is estimated at 5.7.

- Specific capacity and efficiency of the NoVOCs™ well were estimated based on the step-drawdown tests and water injection test conducted at the NoVOCs™ well. The calculated average specific capacities are 1.48 gpm/ft for the upper screened pumping, 1.50 gpm/ft for the upper screened injection, and 3.22 gpm/ft for the lower screened pumping. The calculated average well efficiencies are 82 percent for the upper screened pumping, 97 percent for the upper screened injection, and 91 percent for the lower screened pumping. The 97-percent well efficiency for the upper screened injection is for injection of clean tap water.

- The radius of influence during the constant discharge pumping test (20 gpm) was at least 100 feet based on drawdown measured at the observation wells. No data were collected from the observation well farthest from the pumping well (MW-54), which is 105 feet from the NoVOCs™ well.

- No positive (recharge) or negative (flow barrier) boundaries are evident from the constant discharge pumping test data.

- The injection test results show that the maximum flow of clean tap water that can be injected through the upper screen of the NoVOCs™ well is 25 gpm. At that injection rate, the water level will rise 17 feet and reach the ground surface.

- The video survey of the NoVOCs™ well revealed a manufacturing defect in the upper well screen. The screen slots are unevenly cut, and about 30 percent of the slots do not completely penetrate the PVC casing. This defect affects the well efficiency of the upper screened interval and may reduce the available water level rise in the NoVOCs™ well during recharge to the aquifer through the upper screen.

- The video survey also revealed significant fouling of the NoVOCs™ well screens by iron precipitation and microbiological growth. Such fouling may impair the performance of the NoVOCs™ system by obstructing the well screen and filter pack.

- The findings of the aquifer tests and tidal study of the aquifer treated by the NoVOCs™ system indicate that the aquifer hydraulic conditions are suitable for application of the NoVOCs™ technology. The NoVOCs™ well as designed should be able to extract and inject a flow rate of 20 gpm based on the aquifer hydraulic characteristics.

7.0 REFERENCES

Bechtel National, Inc. (Bechtel). 1996. Final Technical Memorandum, Additional Site Characterization for NoVOCs™ Technology Demonstration at Site 9, Naval Air Station (NAS) North Island, San Diego, California. CTO-0084/0065. March.

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APPENDIX A

LOG OF BORING S9-SB-34
(BECHTEL 1998)

FINAL

BOREHOLE LOG	PROJECT and JOB NUMBER: CLEAN II 22214-146	SHEET NO.: 1 of 4	HOLE NO.: S9-SB-34
DRILLER: West Hazmat Drilling Corp.	SITE and LOCATION: Site 9; NASNI, San Diego	OVERBURDEN	BEGUN: 12-9-97
DRILL MAKE AND MODEL: CME-75	COORDINATES: N 1,833,905.5 E 6,261,875.8 / LOGGED BY: S. Donovan	ROCK (FT)	COMPLETED: 12-9-97
HOLE SIZE DIAMETER: 4.5" / CORE SIZE DIAMETER: 2.5	GROUND ELEV.: 21.2 / DEPTH/ELEV. GROUND WATER: ▽ /21.2 ▼ /21.2 / CHECKED BY: J. Kozakowski	TOTAL DEPTH: 90.0	UPDATE: 9-15-98

Organic Vapor Reading (ppm)		Soil recovery (%)	Sampler / Core Advance (ft)	Blow Count (# blows)	Elevation (MLLW)	Depth (ft)	Description and Classification	Remarks:
						0	Drill to 9' bgs with a tri-cone bit.	
						3		Hand Auger to 5' bgs.
0		100	1.0	N/A	12.2	9	FILL:	
					12.0		SILTY SAND (SM); Orange-brown, medium dense, saturated, very fine- to coarse-grained.	
					11.5		SAND (SP); Gray brown, medium dense, saturated, very fine- to coarse-grained, some shell fragments, some mica.	
0		0	5.0		11.2	10	SAND (SP); Gray, medium dense, saturated, very fine- to fine-grained, some mica.	
							No Recovery	
0		80	2.0	N/A	6.2	15	SILTY SAND (SM); Orange brown, medium dense, saturated, very fine- to fine-grained.	Start of Natural Formation?
5		100	3.0	N/A		17		
10								
8						18	At 18'; SILTY SAND (SM); As above, color change to gray brown.	
					2.2	19	SAND (SP); Gray brown, medium dense, saturated, very fine- to fine-grained.	
8		100	5.0	N/A	1.7		SILTY SAND (SM); Orange brown, dense, moist, very fine- to fine-grained, micaceous.	
					1.2	20	SAND (SP); Light brown gray, medium dense, saturated, very fine-grained, micaceous.	
20					0.2	21	SAND (SP); As above, color change to orange brown.	
					-0.1		SAND (SP); As above, light gray, several 0.25 - 0.5" thick orange brown bedding layers.	
20						23		
20						24		

REGISTERED GEOLOGIST ★ SCOTT L DONOVAN NO. 1969 CERTIFIED ENGINEERING GEOLOGIST ★ STATE OF CALIFORNIA

SS = Split Spoon; HA = Hand Auger; B = Bailer; CB = Core Barrel; HP = Hydropunch	SITE and LOCATION: Site 9; NASNI, San Diego	HOLE NO.: S9-SB-34

FINAL

BOREHOLE LOG	PROJECT and JOB NUMBER		SHEET NO.	HOLE NO.
BECHTEL	CLEAN II	22214-146	2 of 4	S9-SB-34

Organic Vapor Reading (ppm)		Soil recovery (%)	Sampler / Core Advance (ft)	Blow Count (# blows)	Elevation (MLLW)	Depth (ft)	Graphics	Sample depth	Sampler type	Description and Classification	Remarks:
0		100	5.0	N/A	-3.8					SAND (SP); Brownish gray, medium dense, saturated, very fine- to fine-grained, micaceous.	
0						26					
0						27					
0						28					
0						29					
0		100	5.0	N/A		30					
0						31					
0						32				From 32 - 33' bgs, few shell fragments.	
0						33				At 33' bgs, one piece of angular, 1" gravel.	
0						34					
0		70	5.0	N/A	-14.1	35					
					-14.3					CLAY (CL); Brownish gray, stiff, moist, some orange oxidation spots.	
0					-14.6	36				SILTY SAND (SM); Brownish gray, medium dense, saturated, very fine- to fine-grained, some oxidation stringers.	
0						37					
					-16.2					SAND (SP); Brownish gray, medium dense, saturated, very fine- to fine-grained, micaceous.	
0					-16.8	38				From 36.75 to 37' bgs, Some shells with horizontal orientation.	
						39				SILTY SAND (SM); Brown, medium dense, saturated, very fine- to fine-grained, some mica.	
0		100	5.0	N/A	-18.8	40				SAND (SP); Brownish gray, medium dense, saturated, .very fine- to coarse-grained,some mica and shell fragments.	
0						41				SAND (SP); Gray, medium dense, saturated, very fine- to fine-grained, some mica, fine black grains.	
0						42					
0						43					
0						44					
0		100	5.0	N/A		45					
0						46					
0						47					
0						48					
0						49					
0		100	5.0	N/A		50					
0						51					
0						52					
0						53					

SS = Split Spoon; HA = Hand Auger; B = Bailer; CB = Core Barrel; HP = Hydropunch

SITE and LOCATION	HOLE NO.
Site 9; NASNI, San Diego	S9-SB-34

FINAL

BOREHOLE LOG

PROJECT and JOB NUMBER: CLEAN II 22214-146

HOLE NO. S9-SB-34

Organic Vapor Reading (ppm)		Soil recovery (%)	Sampler / Core Advance (ft)	Blow Count (# blows)	Elevation (MLLW)	Depth (ft)	Description and Classification	Remarks:
0						54	SAND (SP); Gray, medium dense, saturated, very fine- to fine-grained, some mica, fine black grains.	
0		95	5.0	N/A		55		
0						56		
0						57		
0						58		
0						59	From 58.5 to 60.25' bgs, SAND (SP); As above, 20% shell fragments with some horizontal bedding.	
0		25	1.0	N/A	-39.1	60	At 60' bgs, Difficult drilling, dense sand. No Recovery.	
0		100	4.0	N/A	-39.8	61	SAND (SP); Light gray, medium dense, saturated, very fine- to fine-grained, some mica and black grains.	
0						62		
0						63	SAND (SP); As above, with shell fragments.	
0						64		
0		5	1.0	N/A		65	Very dense sand to 66' bgs.	
1-10		90	2.0	N/A		66	From 66.25 to 66.75' bgs, dense sand.	
						67	At 66.75' bgs, SAND (SP); As above, medium dense.	
50		100	2.0	N/A		68		
						69		
10		100	3.0	N/A		70		
50						71		
100						72		
100		90	2.0	N/A		73		
30								
50						74		
65		90	5.0	N/A		75		
						76	From 76 to 79' bgs, SAND (SP); As above, brownish gray.	
70						77		
						78	From 78 to 79' bgs, SAND (SP); As above, gray, few shell fragments.	
					-57.8	79	SILTY SAND (SM); Olive gray, dense, saturated, very fine- to coarse-grained.	
30		80	5.0	N/A	-58.8	80	Some pieces of cemented sandstone. SILTY SAND (SM); Pale yellowish brown, dense, saturated, very fine- to fine-grained, few coarse grains.	
15						81		
						82		

SS = Split Spoon; HA = Hand Auger; B = Bailer; CB = Core Barrel; HP = Hydropunch

SITE and LOCATION: Site 9; NASNI, San Diego

HOLE NO. S9-SB-34

FINAL

BOREHOLE LOG	PROJECT and JOB NUMBER		SHEET NO.	HOLE NO.
BECHTEL	CLEAN II	22214-146	4 of 4	S9-SB-34

Organic Vapor Reading (ppm)		Soil recovery (%)	Sampler / Core Advance (ft)	Blow Count (# blows)	Elevation (MLLW)	Depth (ft)	Graphics	Sample depth	Sampler type	Description and Classification	Remarks:
15					-61.2					SILT (ML); Brown, soft, saturated, 0.1" thick layer.	
15					-61.3	83				SILTY SAND (SM); Olive gray, medium dense, saturated, very fine- to fine-grained, some mica, few shell fragments.	
15						84					
20		100	5.0	N/A		85				From 85.5 to 85.75' bgs, As above, coarse-grained, 0.1" thick layer of cemented sandstone fragments.	
					-64.8	86				SAND (SP); Yellow brown, medium dense, saturated, very fine- to medium-grained, with medium shell fragments.	Approximately 165 gallons of grout tremied through outer casing to abandon borehole.
						87					
10					-66.6	88				SAND (SP); Gray, medium dense, saturated, very fine- to fine-grained, some mica.	
					-67.1					SAND (SP); As above, yellow brown.	
					-68.0	89				1" thick SANDSTONE layer, light gray brown.	
					-68.0					From 89.15 to 90' bgs; Sandstone fragments.	
15					-68.8	90					

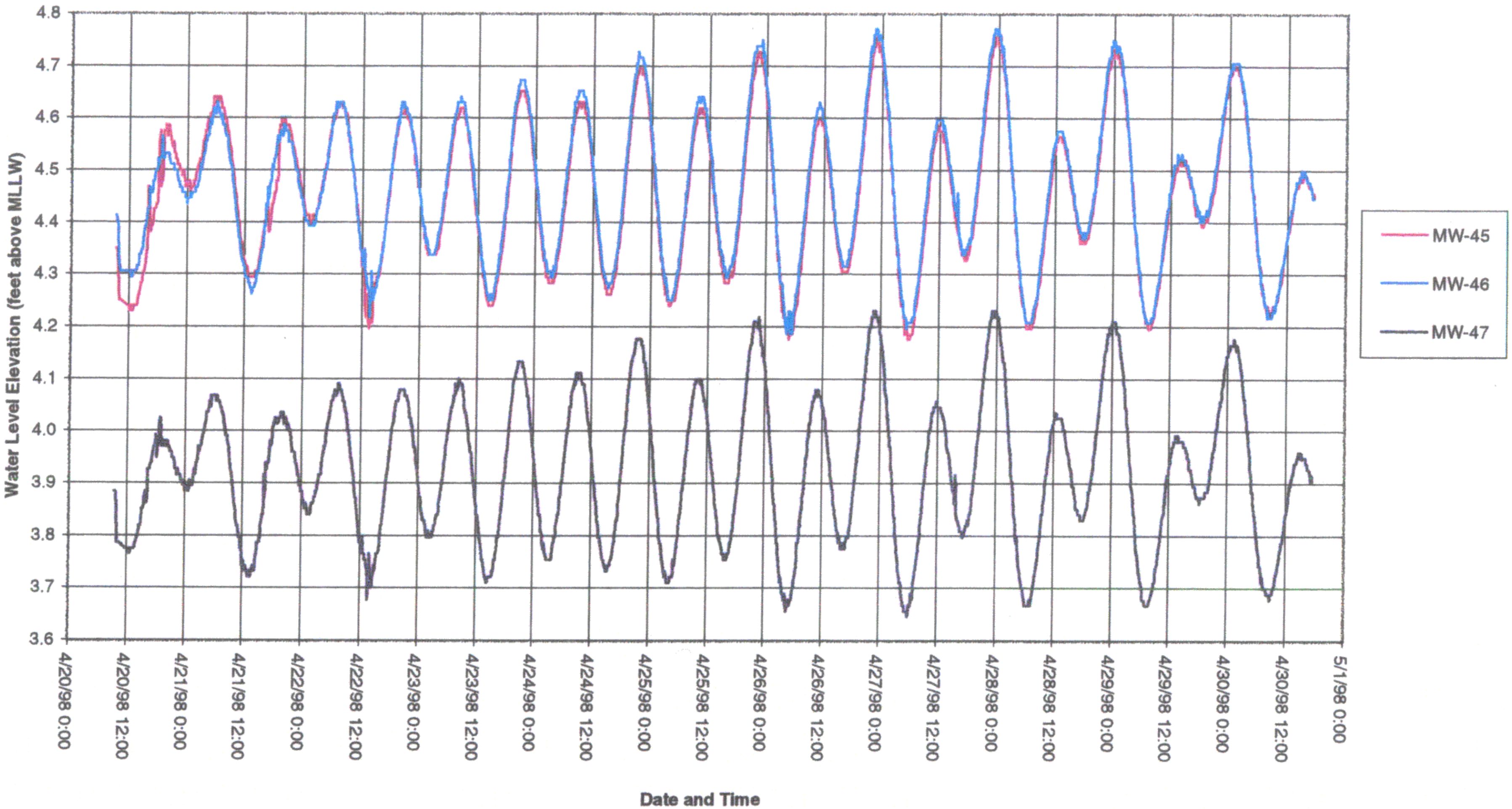
TOTAL DEPTH = 90.0 FEET

SS = Split Spoon; HA = Hand Auger; B = Bailer; CB = Core Barrel; HP = Hydropunch

SITE and LOCATION	HOLE NO.
Site 9; NASNI, San Diego	S9-SB-34

APPENDIX B

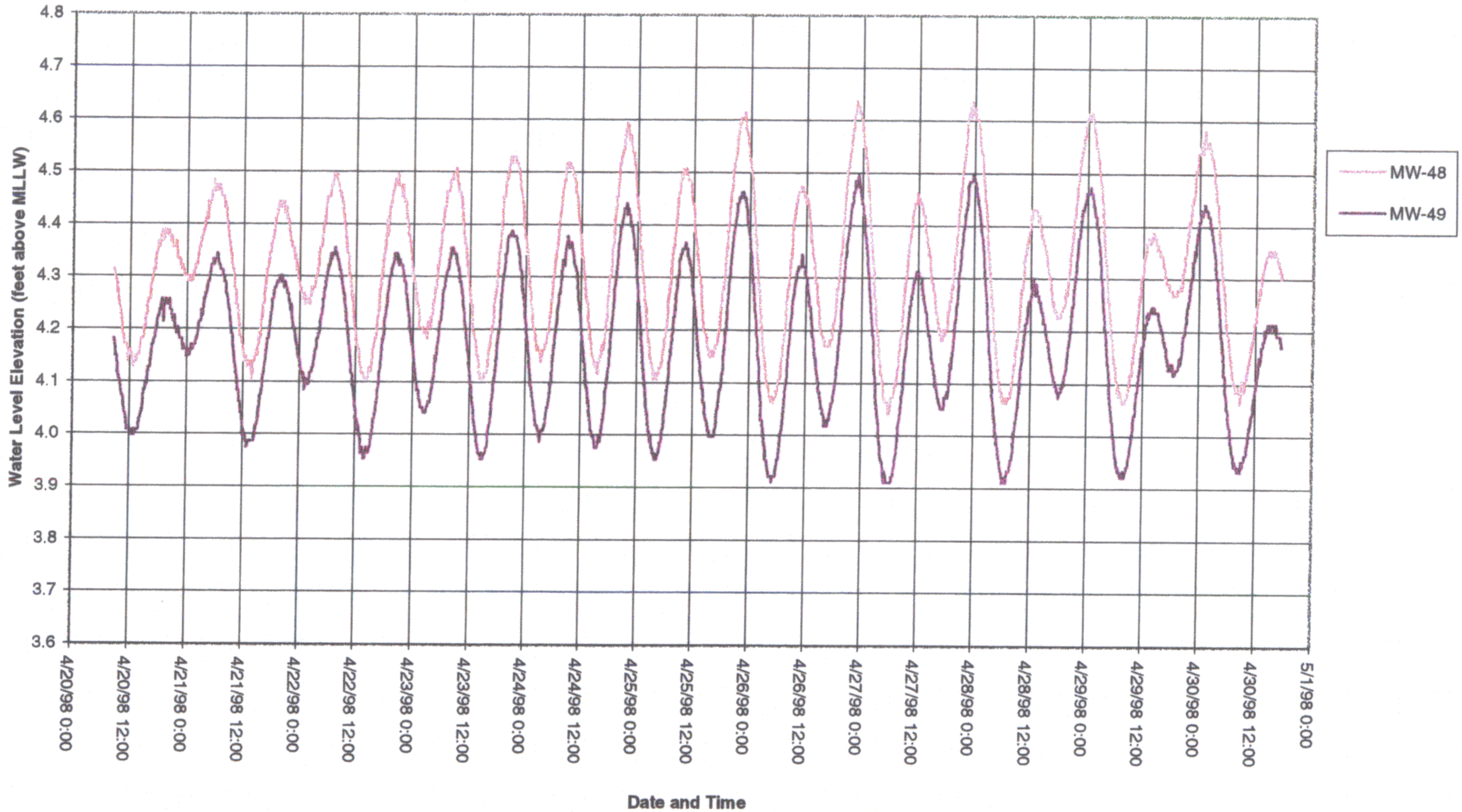
HYDROGRAPHS
TIDAL STUDY



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B1
TIDAL STUDY
MONITORING WELLS MW-45, MW-46, AND MW-47
APRIL 20 THROUGH 30, 1998

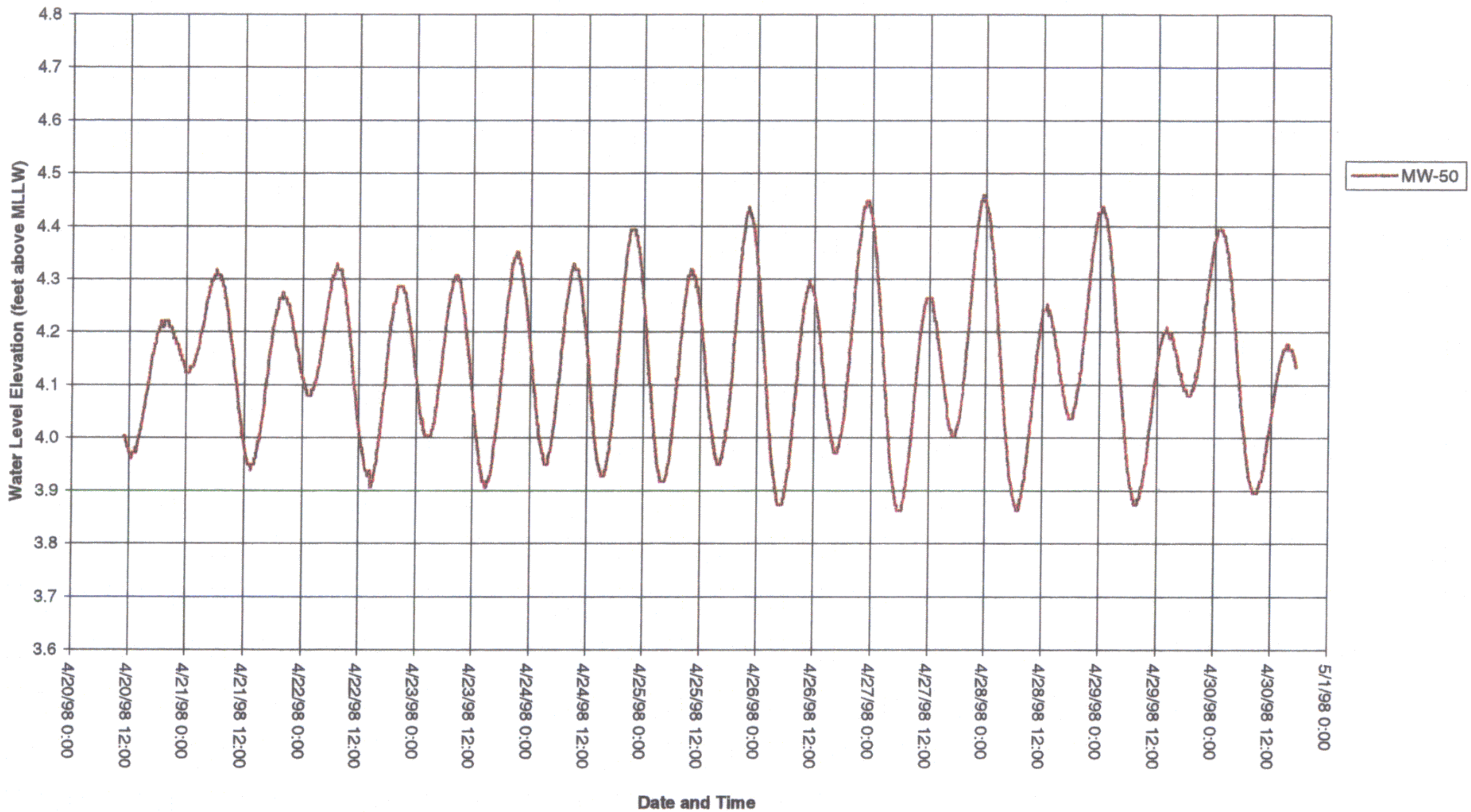
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B2
TIDAL STUDY
MONITORING WELLS MW-48 AND MW-49
APRIL 20 THROUGH 30, 1998

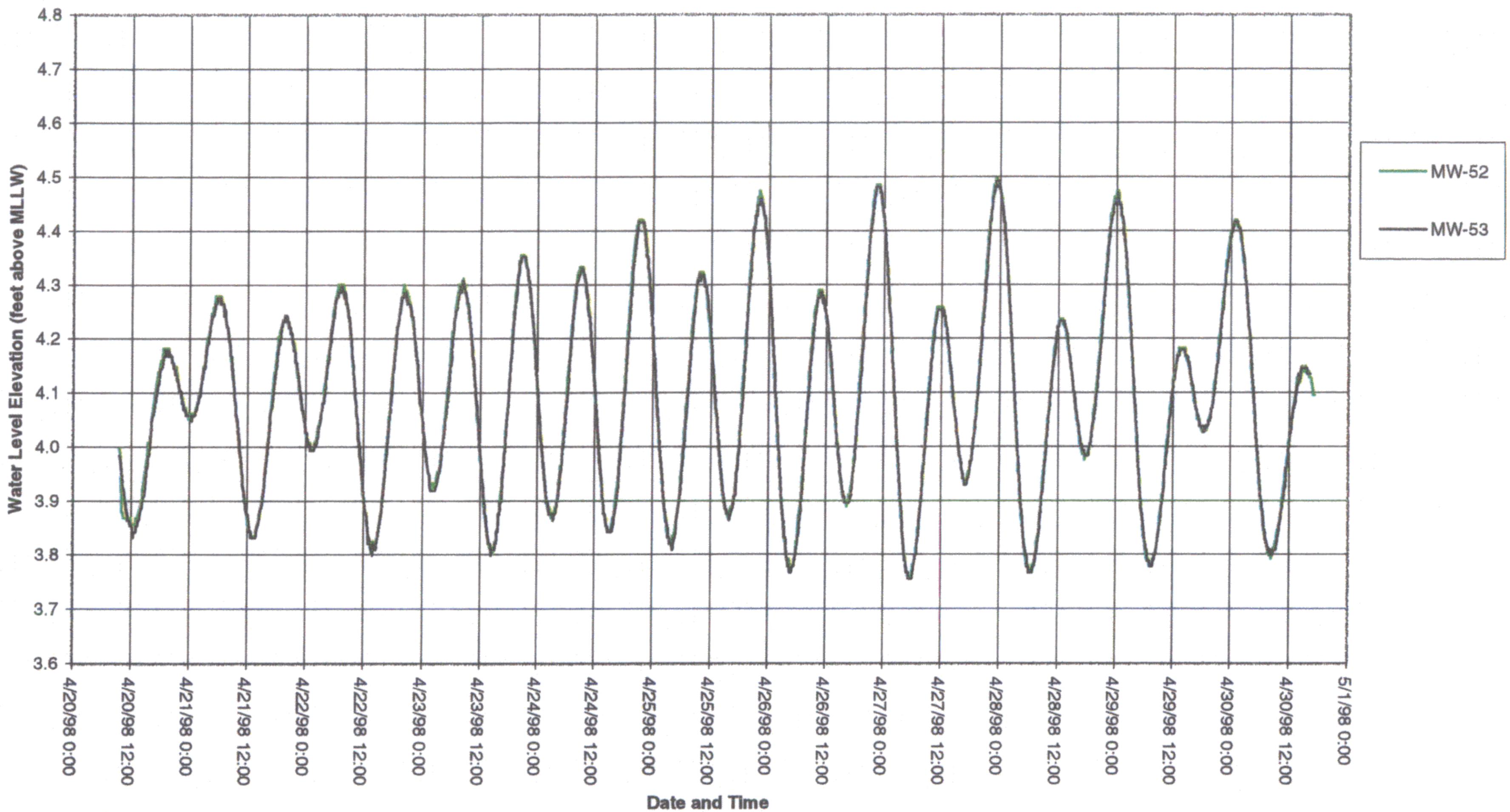
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B3
TIDAL STUDY
MONITORING WELL MW-50
APRIL 20 THROUGH 30, 1998

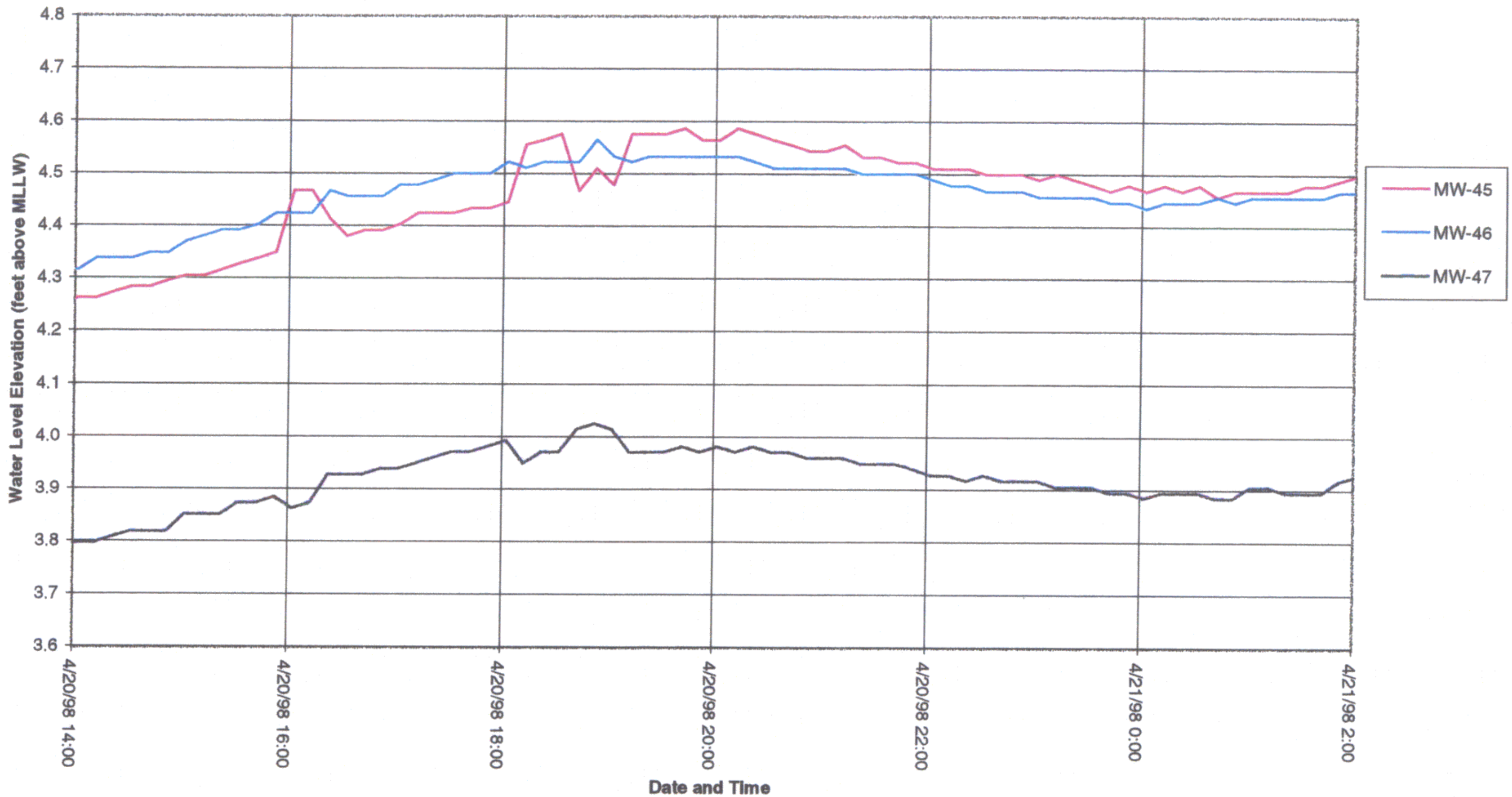
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B4
TIDAL STUDY
MONITORING WELLS MW-52 AND MW-53
APRIL 20 THROUGH 30, 1998

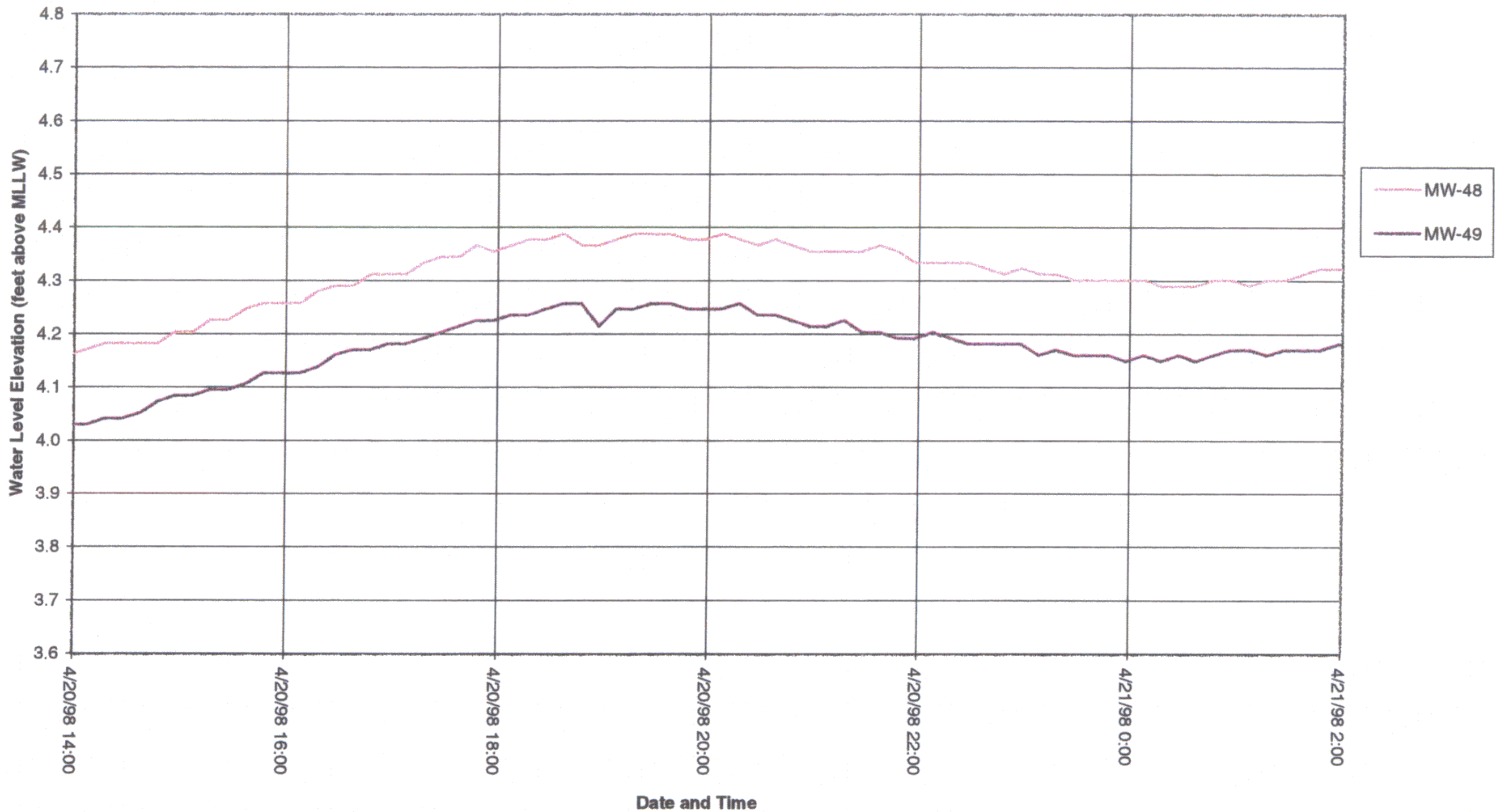
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B5
TIDAL STUDY
MONITORING WELLS MW-45, MW-46, AND MW-47
APRIL 20 AND 21, 1998 (NoVOCs System Startup)

Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9

NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

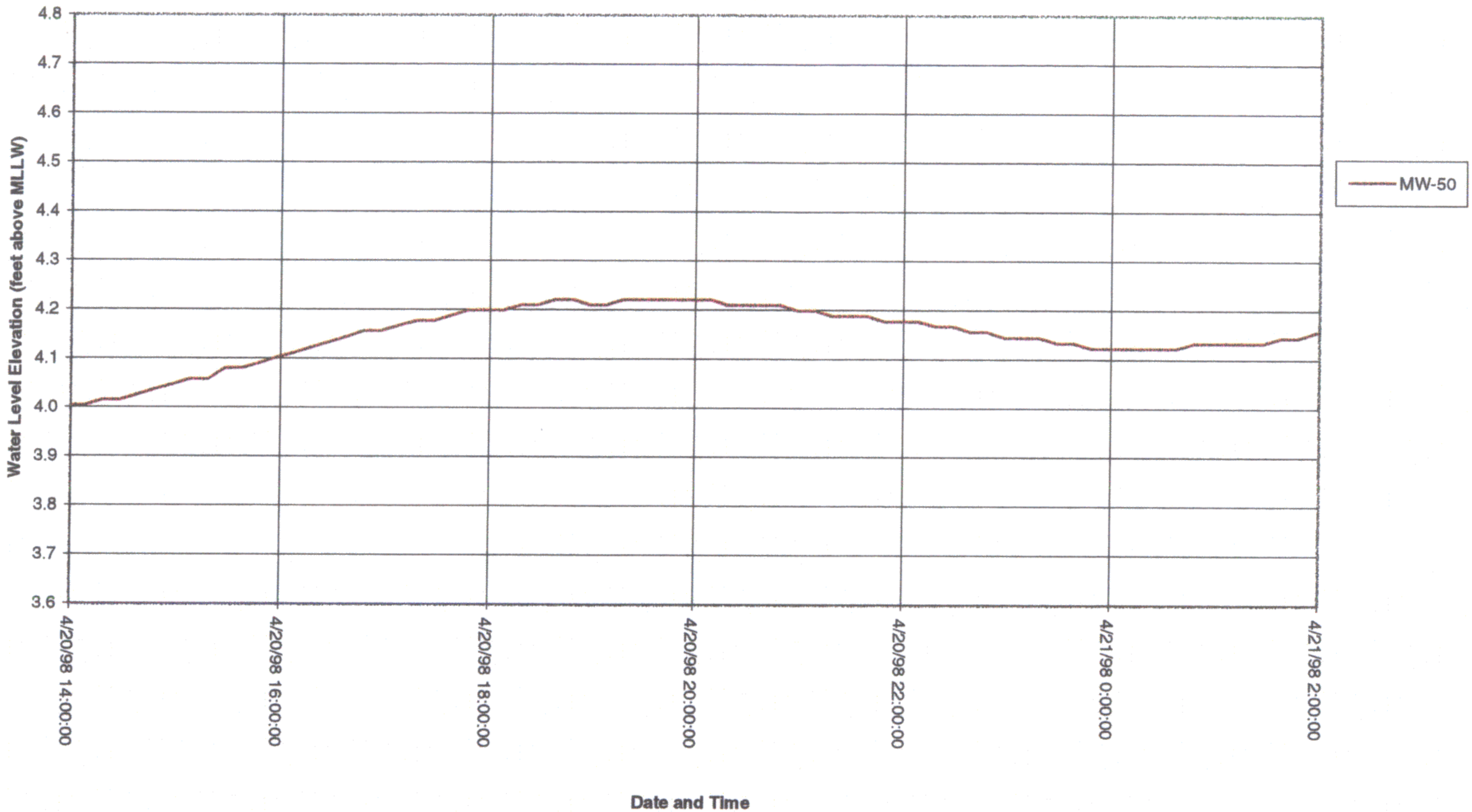
FIGURE B6

TIDAL STUDY

MONITORING WELLS MW-48 AND MW-49

APRIL 20 AND 21, 1998 (NoVOCs Sytem Startup)

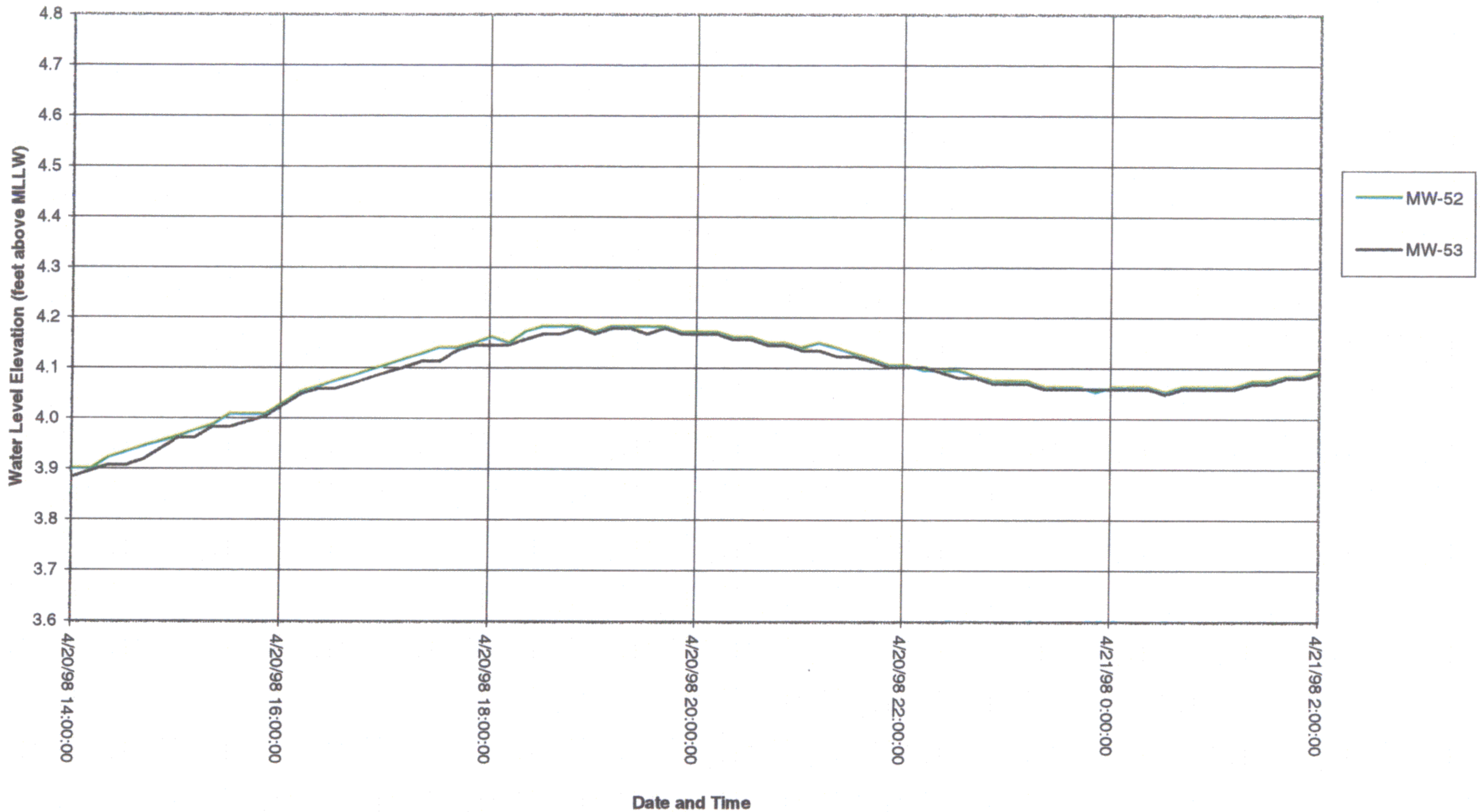
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B7
TIDAL STUDY
MONITORING WELL MW-50
APRIL 20 AND 21, 1998 (NoVOCs System Startup)

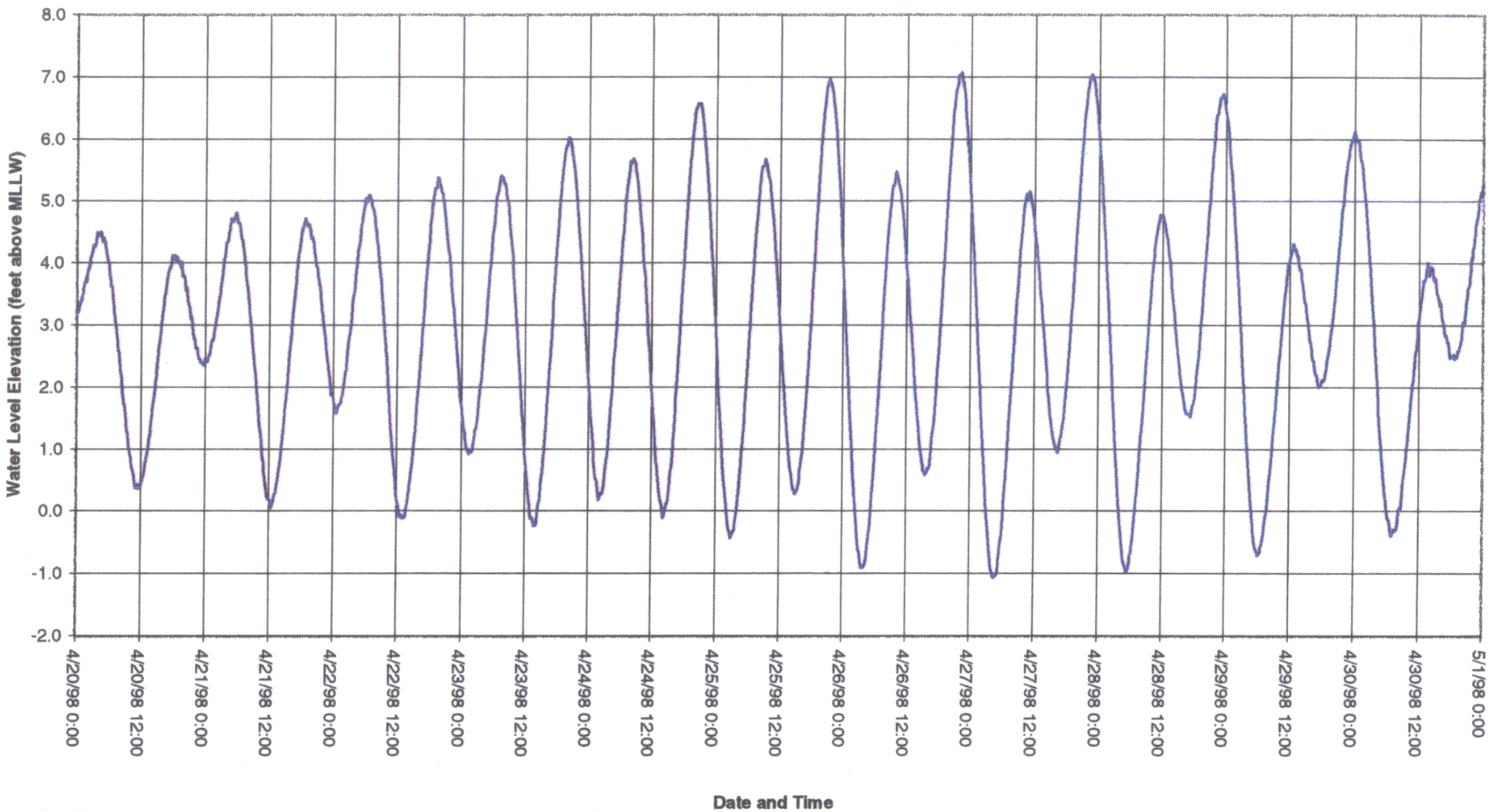
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B8
TIDAL STUDY
MONITORING WELL MW-52 AND MW-53
APRIL 20 AND 21, 1998 (NoVOCs System Startup)

Tetra Tech EM Inc.



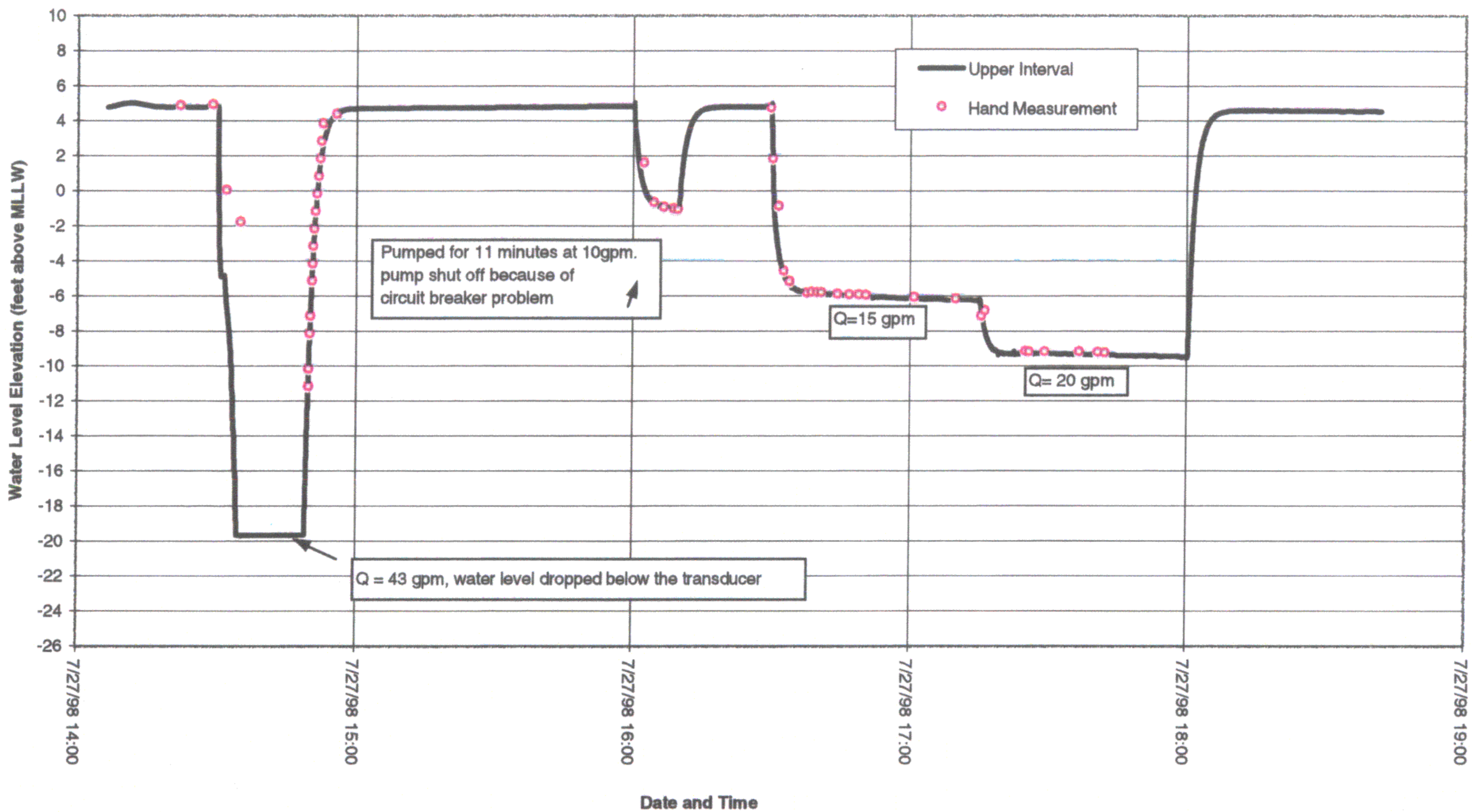
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE B9
TIDAL STUDY
SAN DIEGO BAY SURFACE WATER LEVEL
APRIL 20 THROUGH 30, 1998

Tetra Tech EM Inc.

APPENDIX C

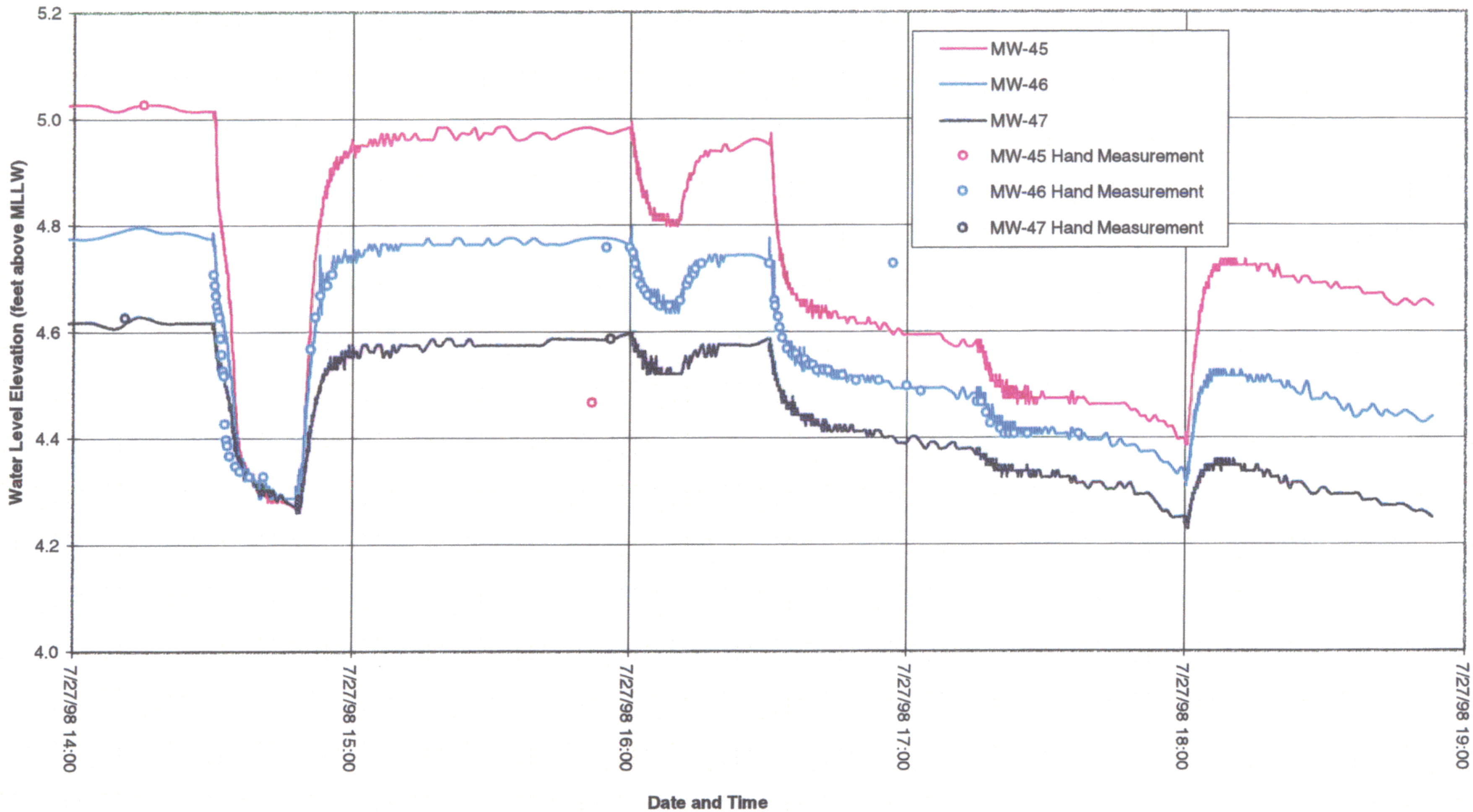
HYDROGRAPHS
STEP DRAWDOWN TEST
UPPER SCREEN INTERVAL



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE C1
STEP DRAWDOWN TEST-UPPER SCREEN INTERVAL
PUMPING WELL
JULY 27, 1998

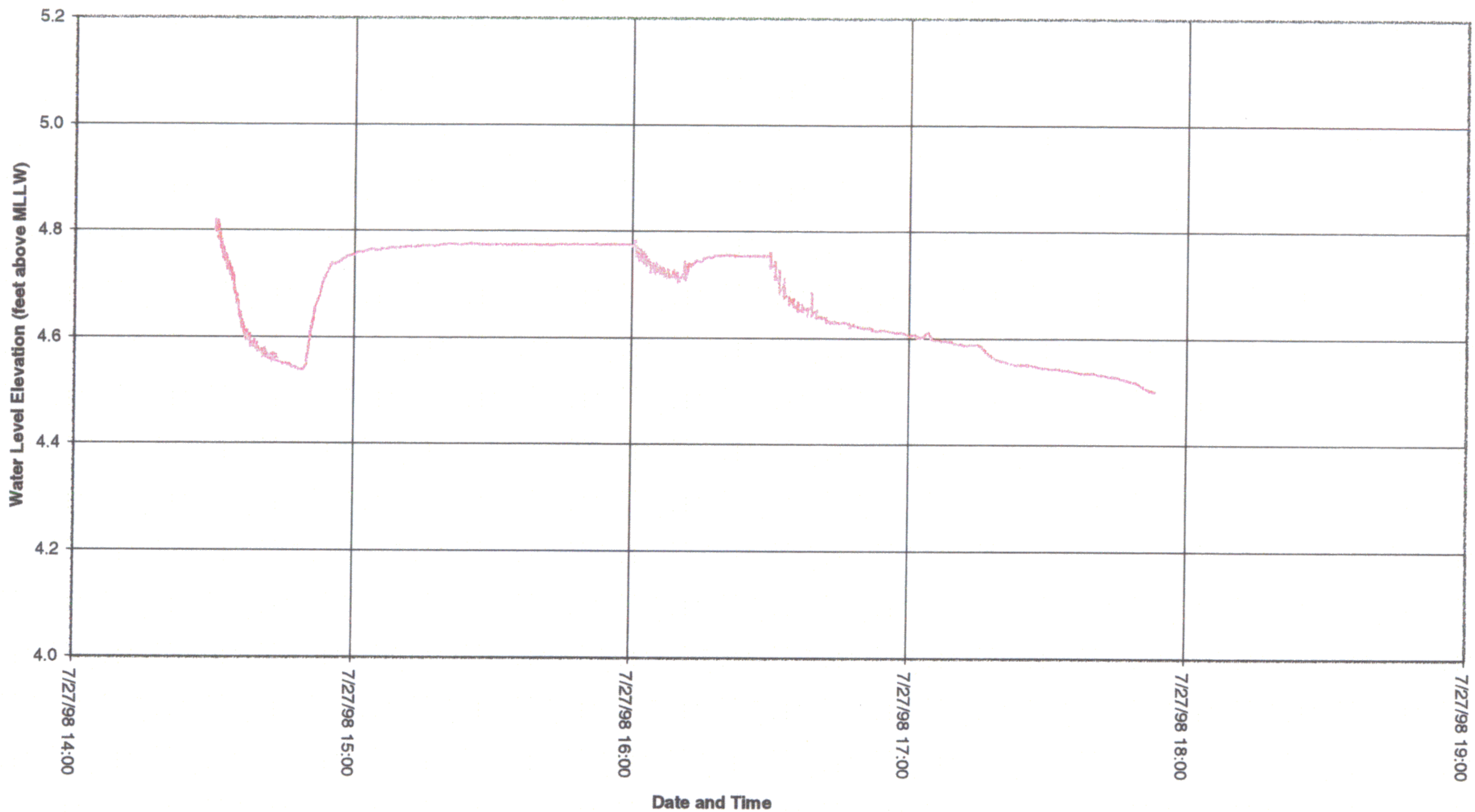
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE C2
STEP DRAWDOWN TEST-UPPER SCREEN INTERVAL
MONITORING WELLS MW-45, MW-46, AND MW-47
JULY 27, 1998

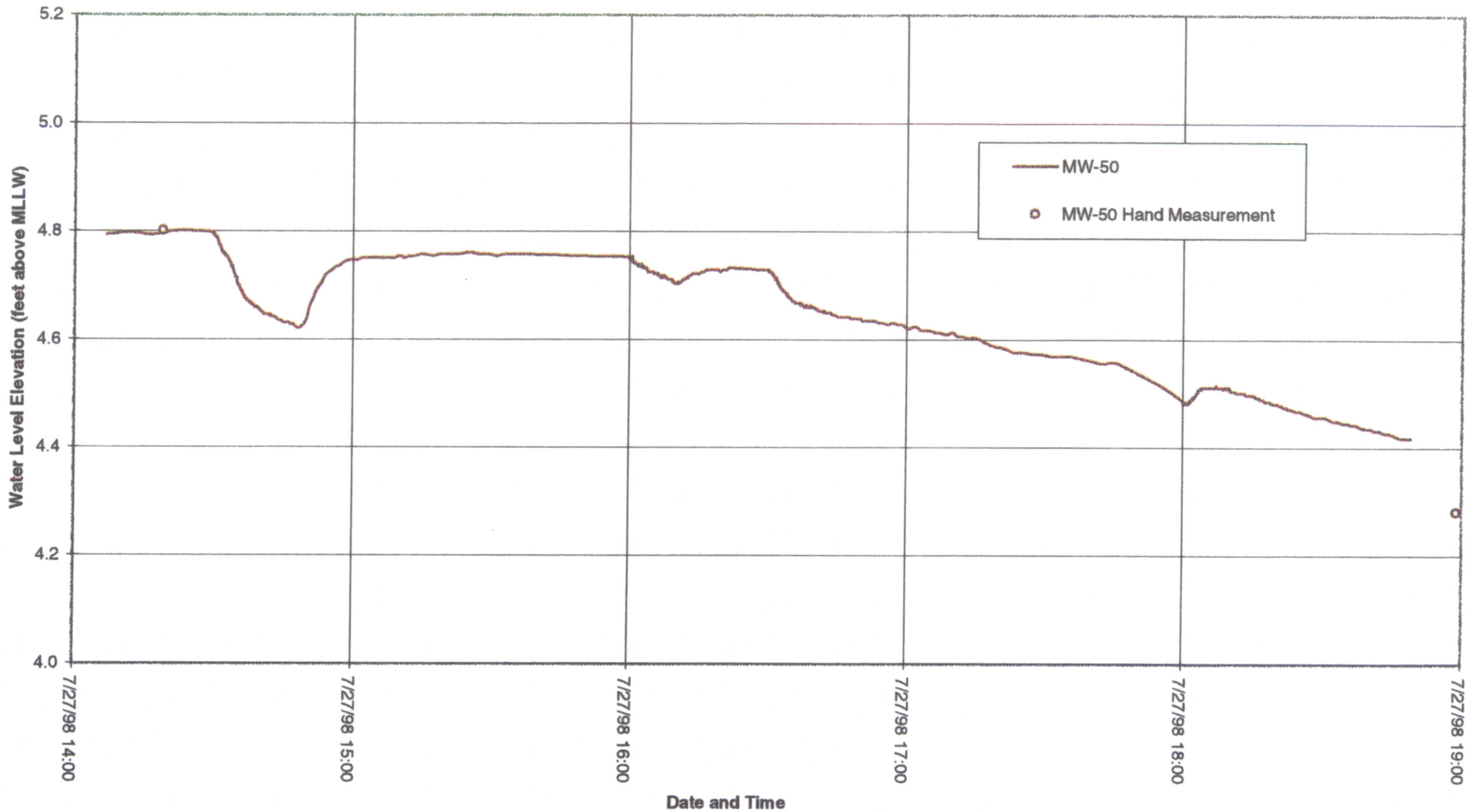
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE C3
STEP DRAWDOWN TEST-UPPER SCREEN INTERVAL
MONITORING WELL MW-48
JULY 27, 1998

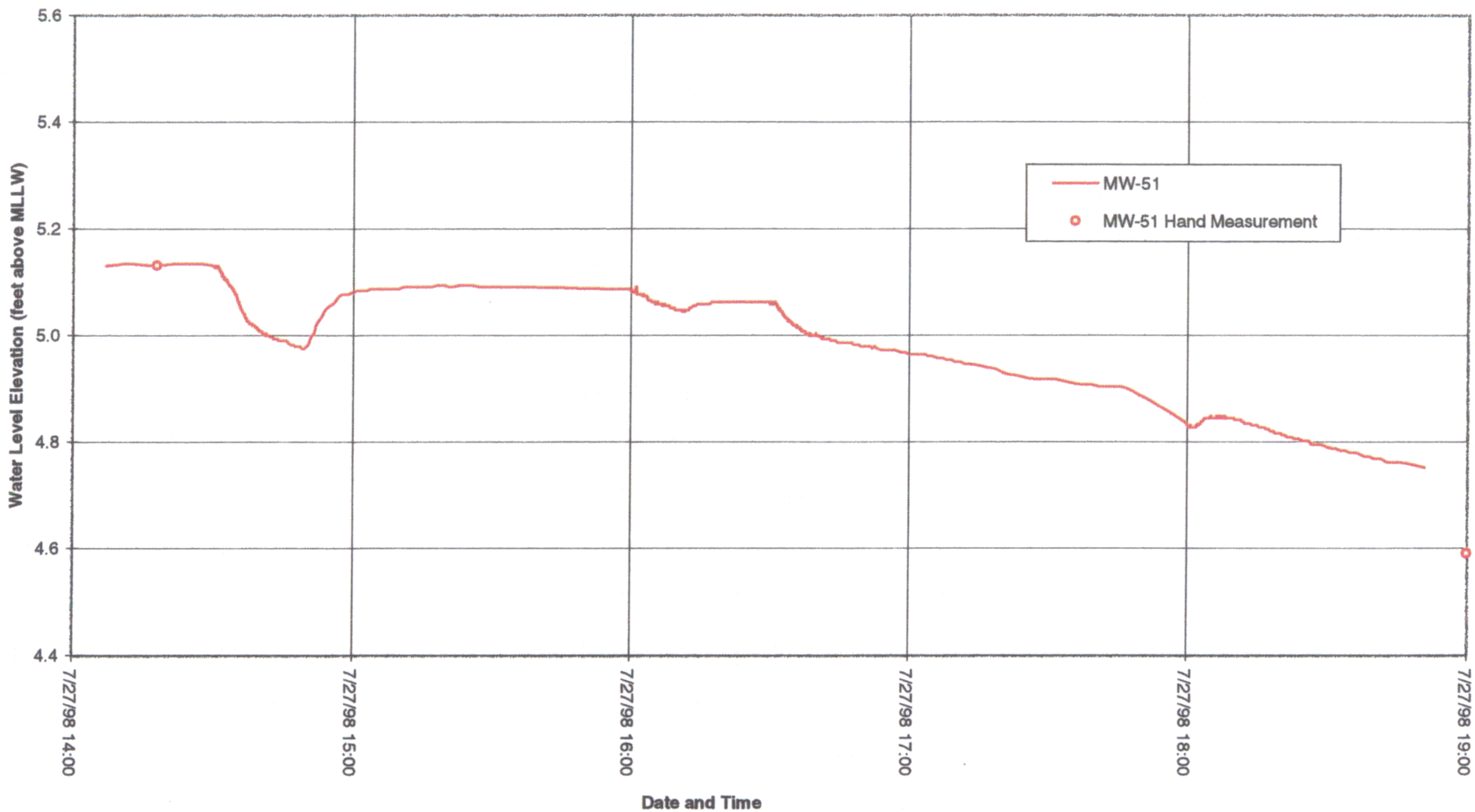
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE C4
STEP DRAWDOWN TEST-UPPER SCREEN INTERVAL
MONITORING WELL MW-50
JULY 27, 1998

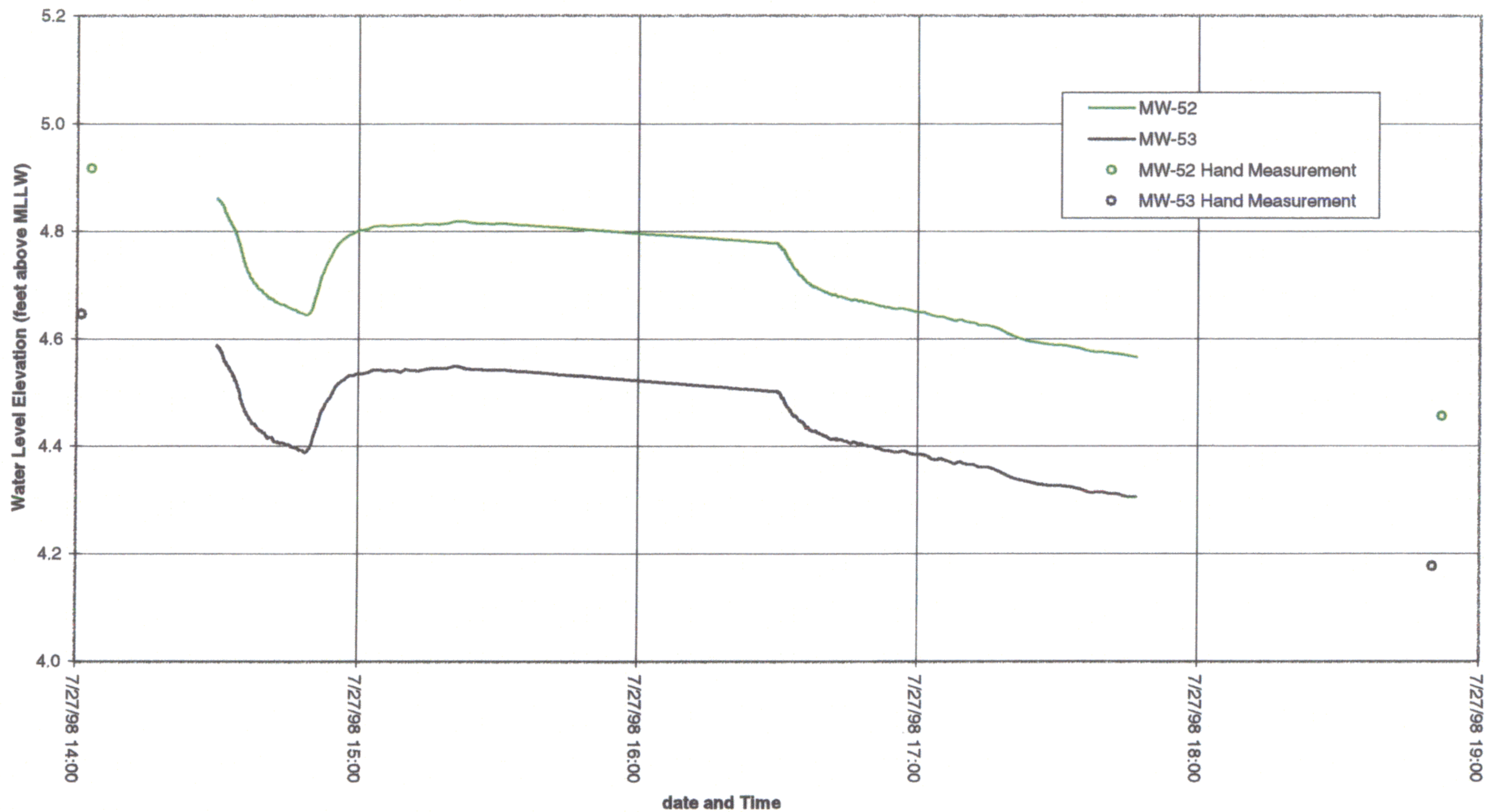
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE C5
STEP DRAWDOWN TEST-UPPER SCREEN INTERVAL
MONITORING WELL MW-51
JULY 27, 1998

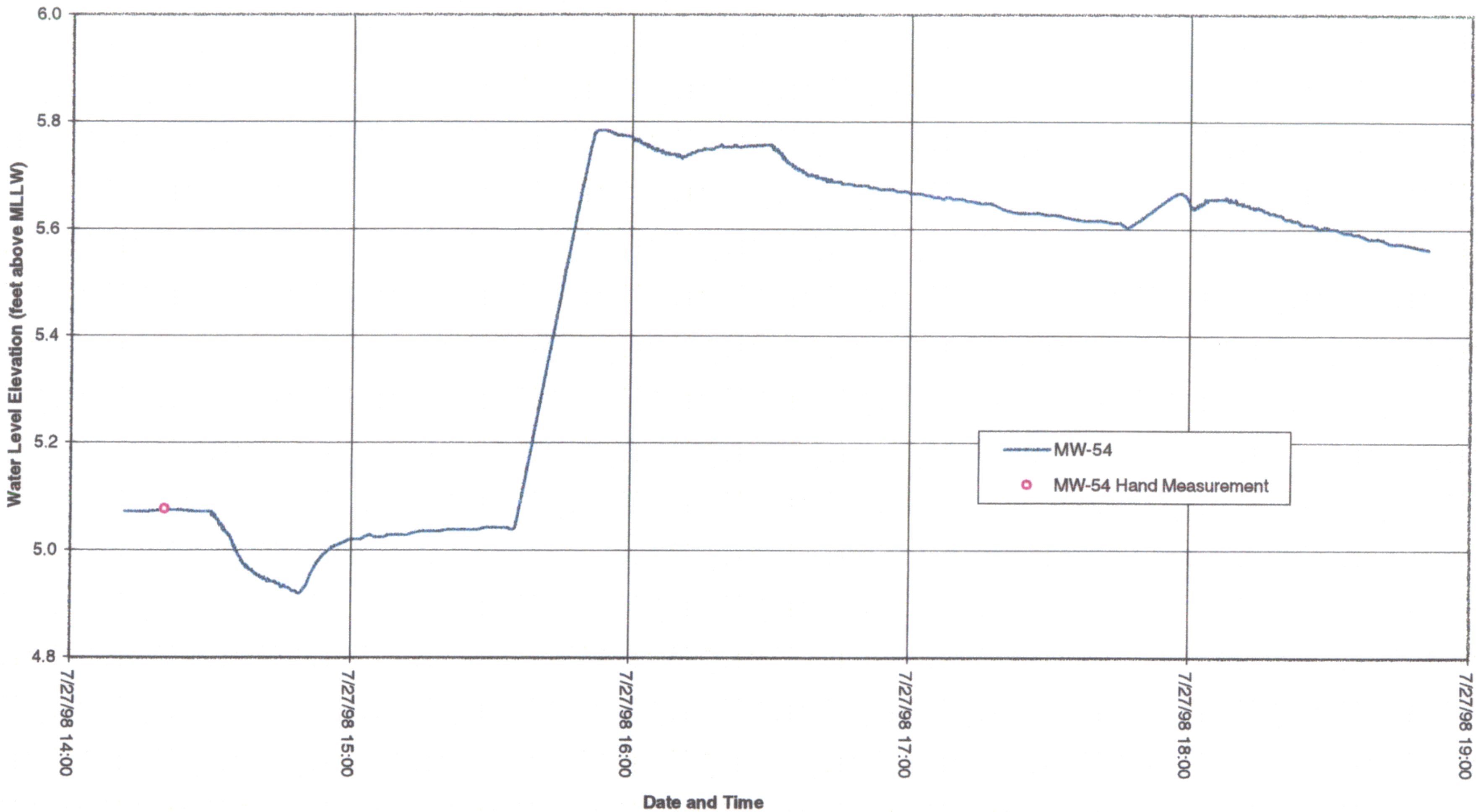
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE C6
STEP DRAWDOWN TEST-UPPER SCREEN INTERVAL
MONITORING WELLS MW-52 AND MW-52
JULY 27, 1998

Tetra Tech EM Inc.



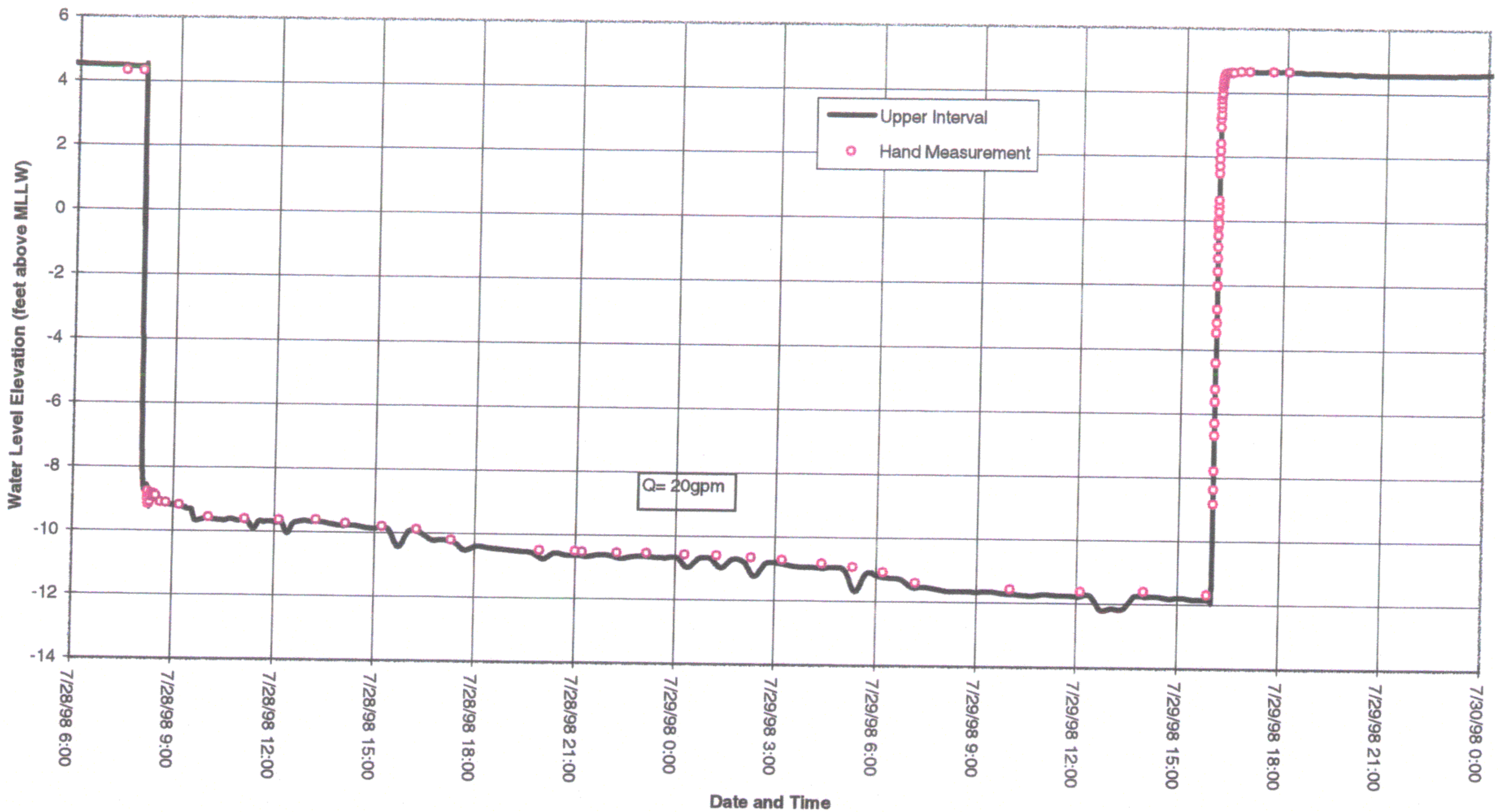
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE C7
STEP DRAWDOWN TEST-UPPER SCREEN INTERVAL
MONITORING WELL MW-54
JULY 27, 1998

Tetra Tech EM Inc.

APPENDIX D

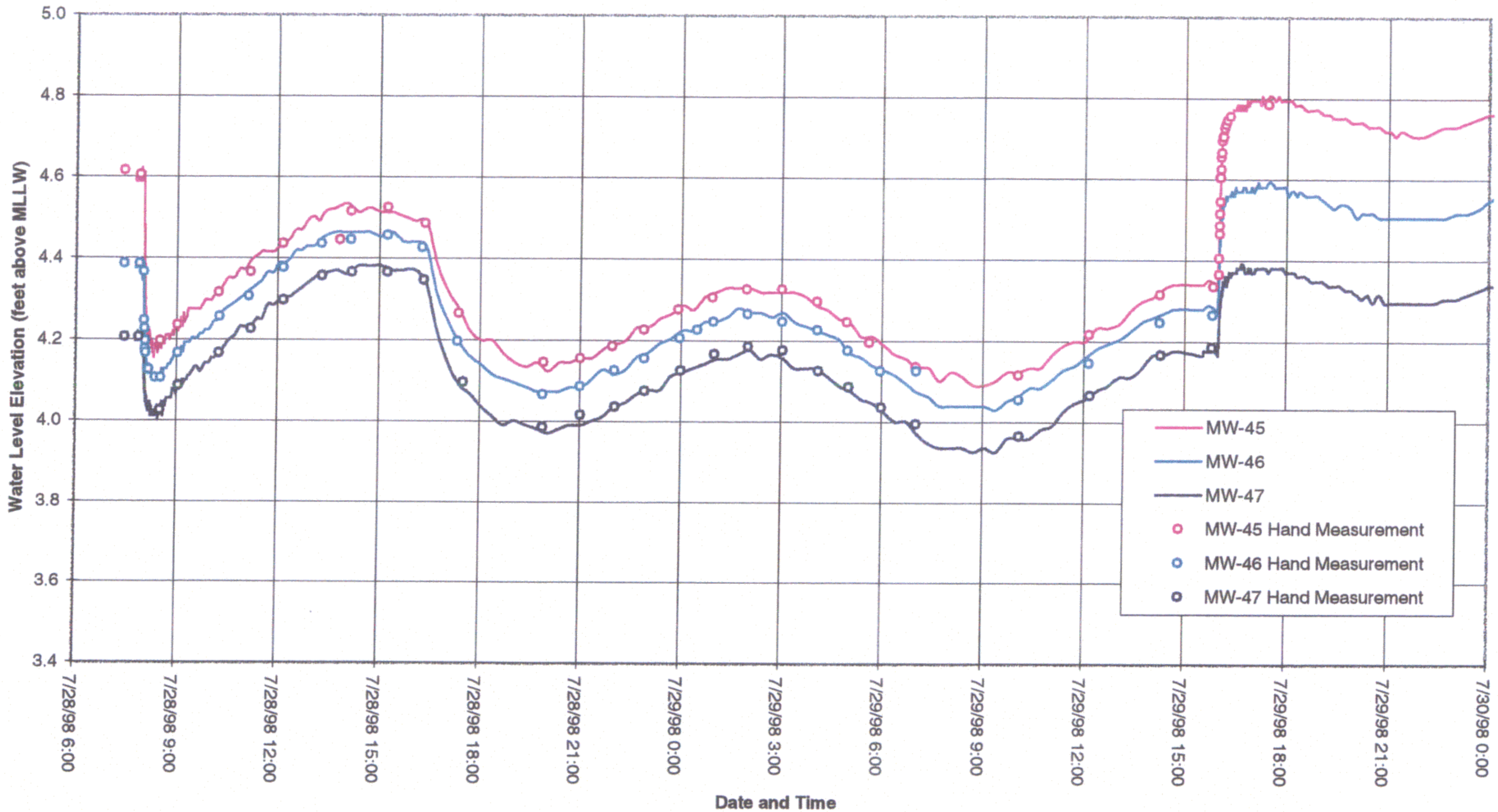
HYDROGRAPHS
CONSTANT DISCHARGE PUMPING TEST
UPPER SCREEN INTERVAL



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE D1
CONSTANT RATE PUMPING TEST
OF UPPER SCREEN INTERVAL
PUMPING WELL
JULY 28 THROUGH 30, 1998

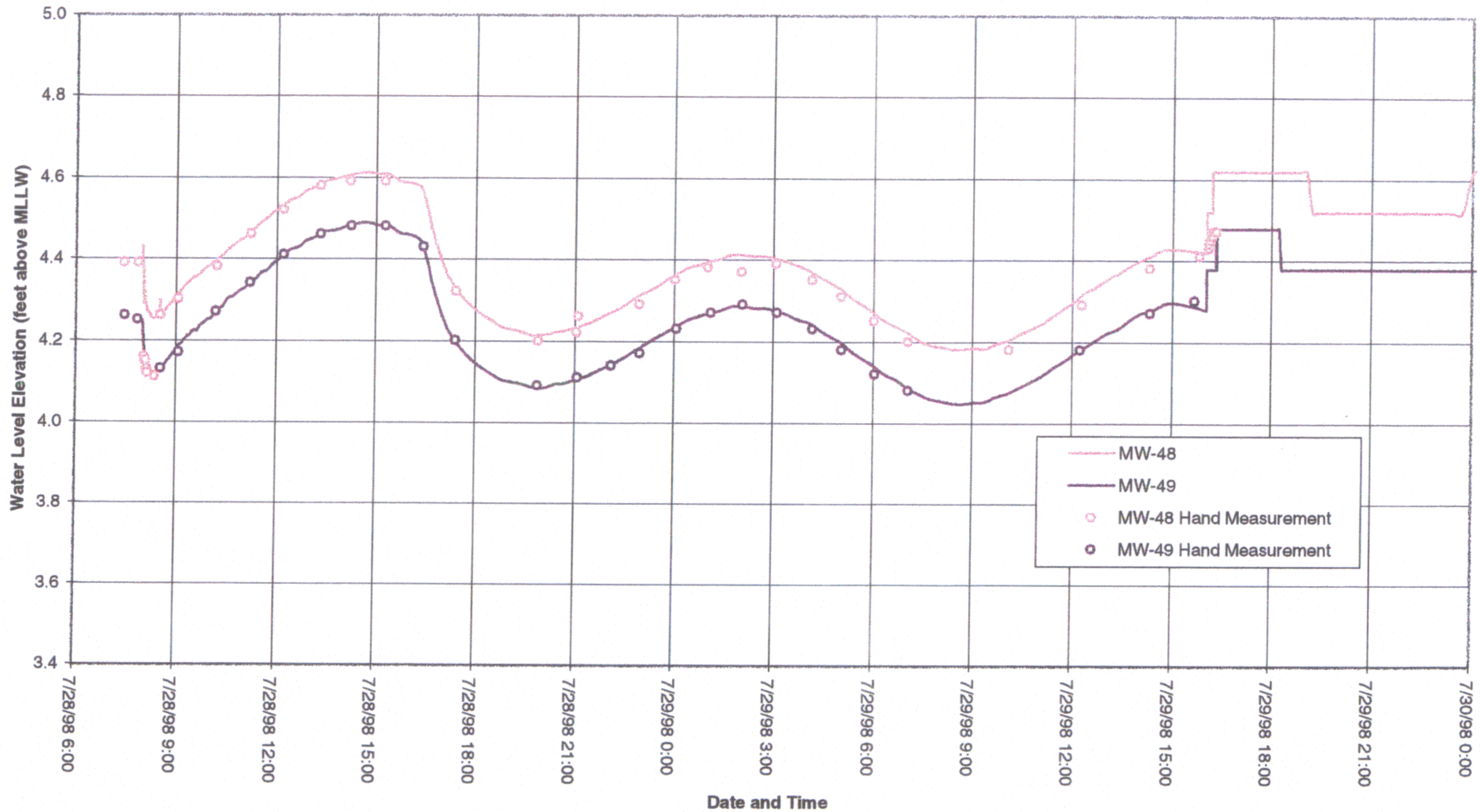
Tetra Tech EM Inc.



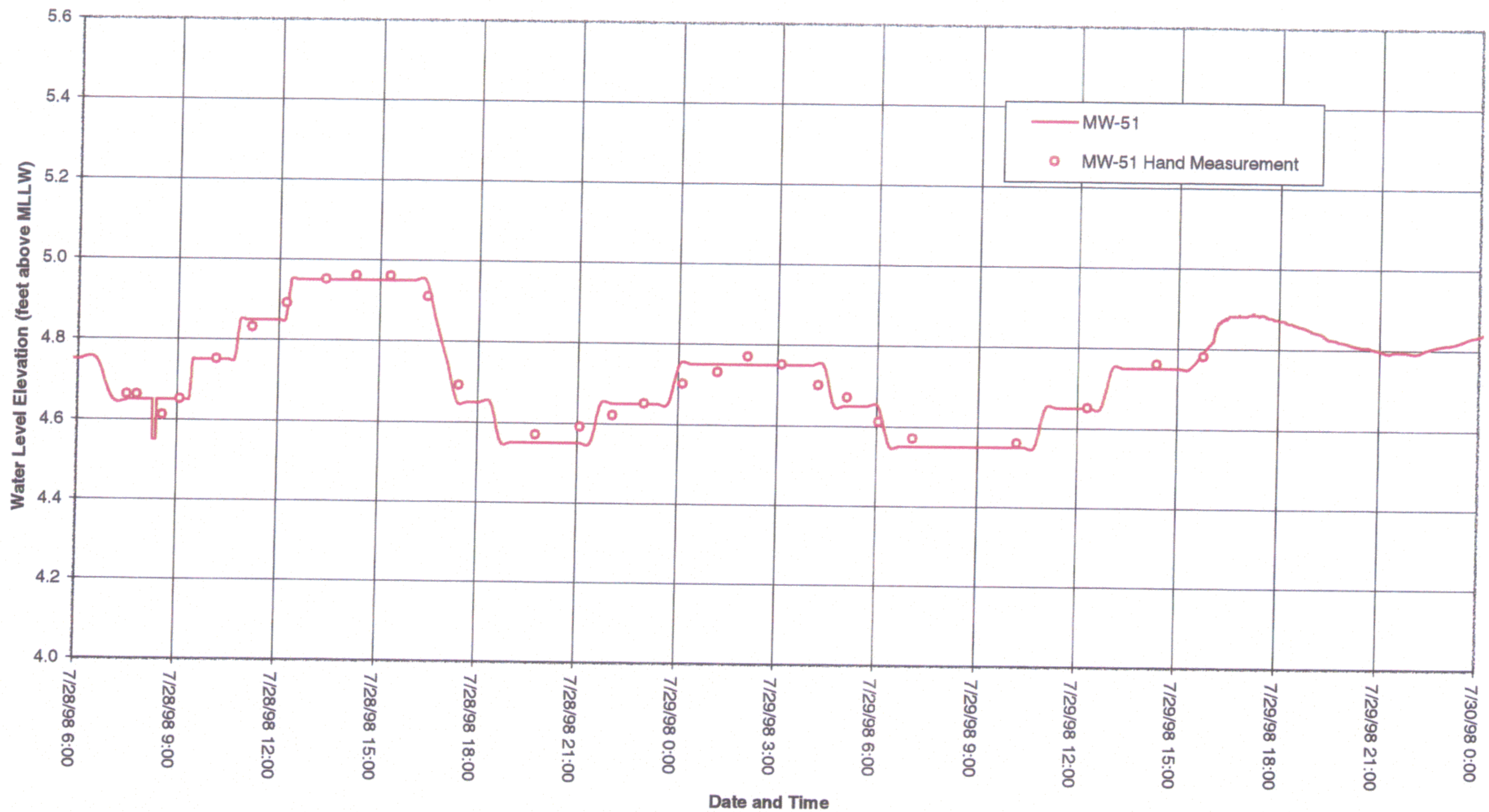
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE D2
CONSTANT RATE PUMPING TEST
OF UPPER SCREEN INTERVAL
MONITORING WELLS MW-45, MW-46, AND MW-47
JULY 28 THROUGH 30, 1998

Tetra Tech EM Inc.



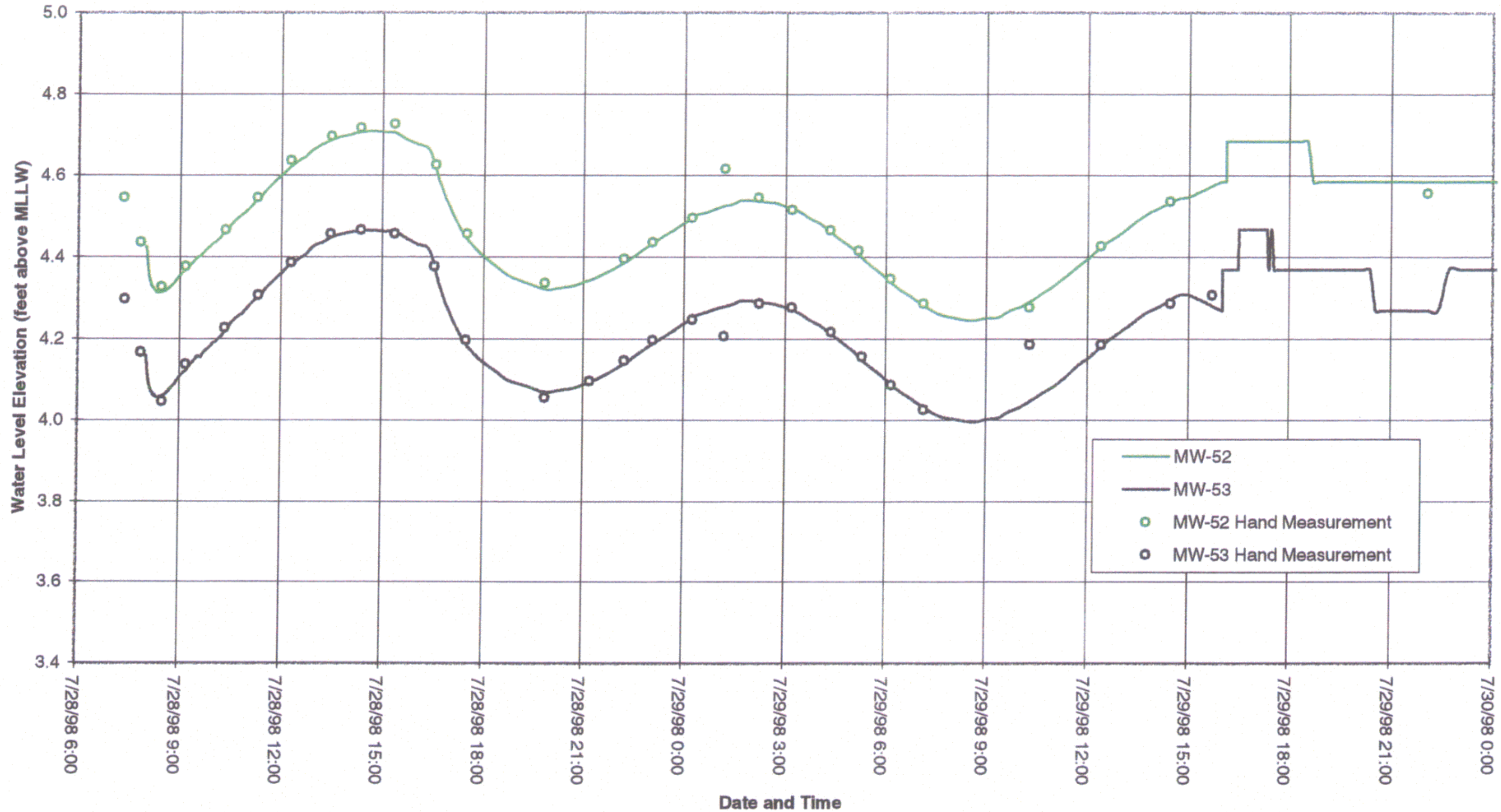
NAS NORTH ISLAND SITE 9 NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
FIGURE D3 **CONSTANT RATE PUMPING TEST** **OF UPPER SCREEN INTERVAL** **MONITORING WELLS MW-48 AND MW-49** **JULY 28 THROUGH 30, 1998**
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE D4
CONSTANT RATE PUMPING TEST
OF UPPER SCREEN INTERVAL
MONITORING WELL MW-51
JULY 28 THROUGH 30, 1998

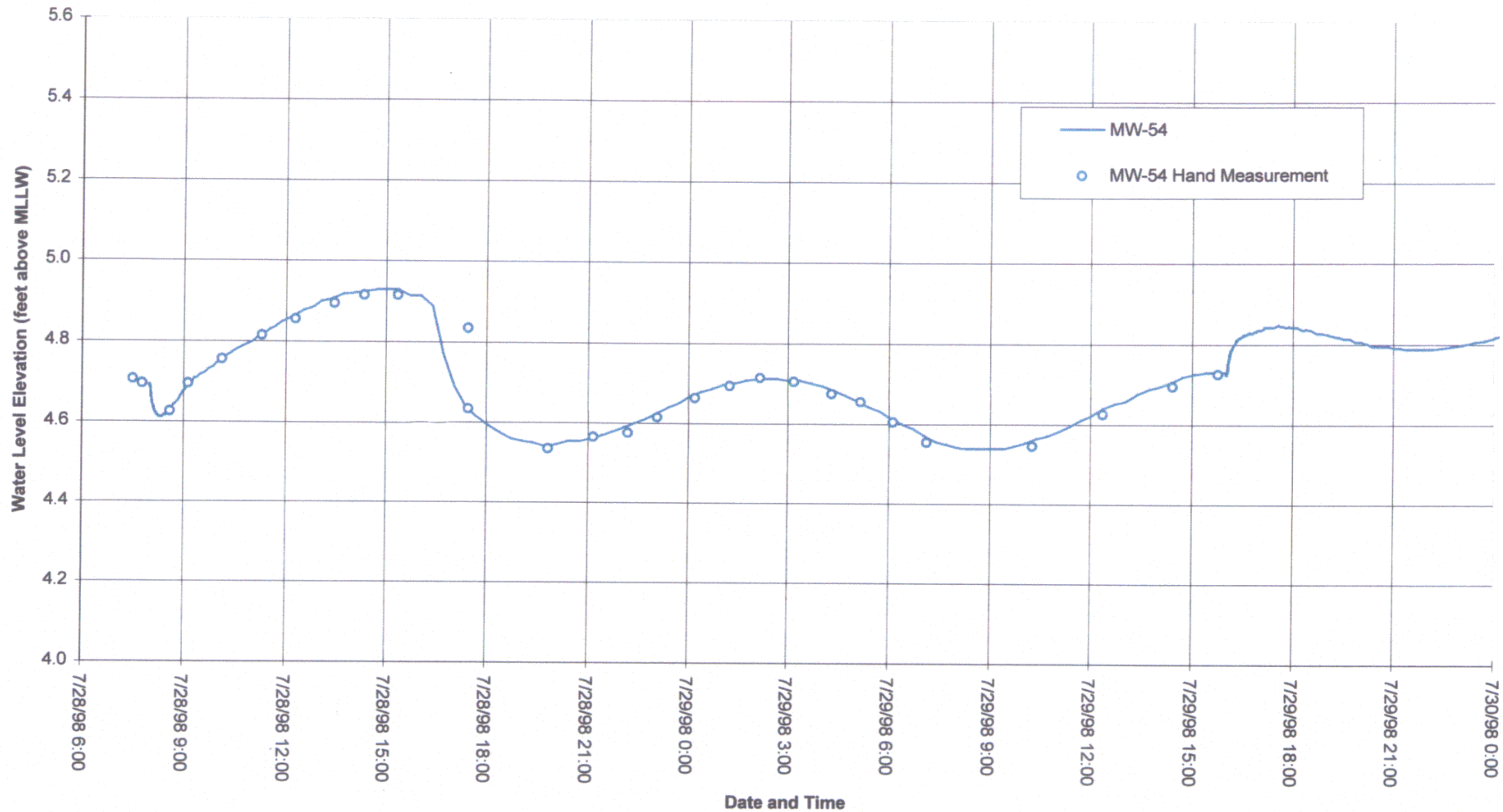
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE D5
CONSTANT RATE PUMPING TEST OF UPPER SCREEN INTERVAL MONITORING WELLS MW-52 AND MW-53 JULY 28 THROUGH 30, 1998

Tetra Tech EM Inc.



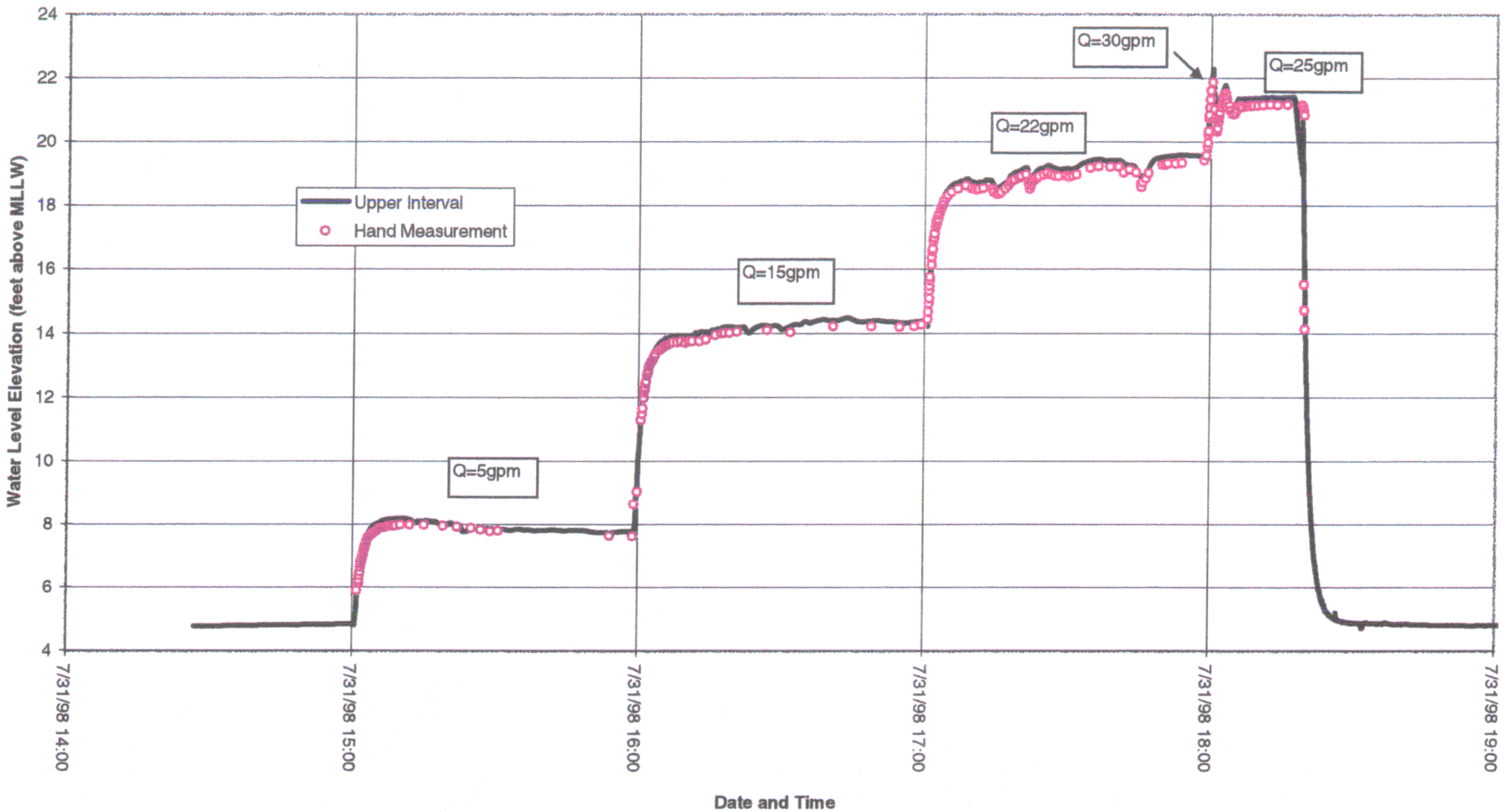
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE D6
CONSTANT RATE PUMPING TEST
OF UPPER SCREEN INTERVAL
MONITORING WELL MW-54
JULY 28 THROUGH 30, 1998

Tetra Tech EM Inc.

APPENDIX E

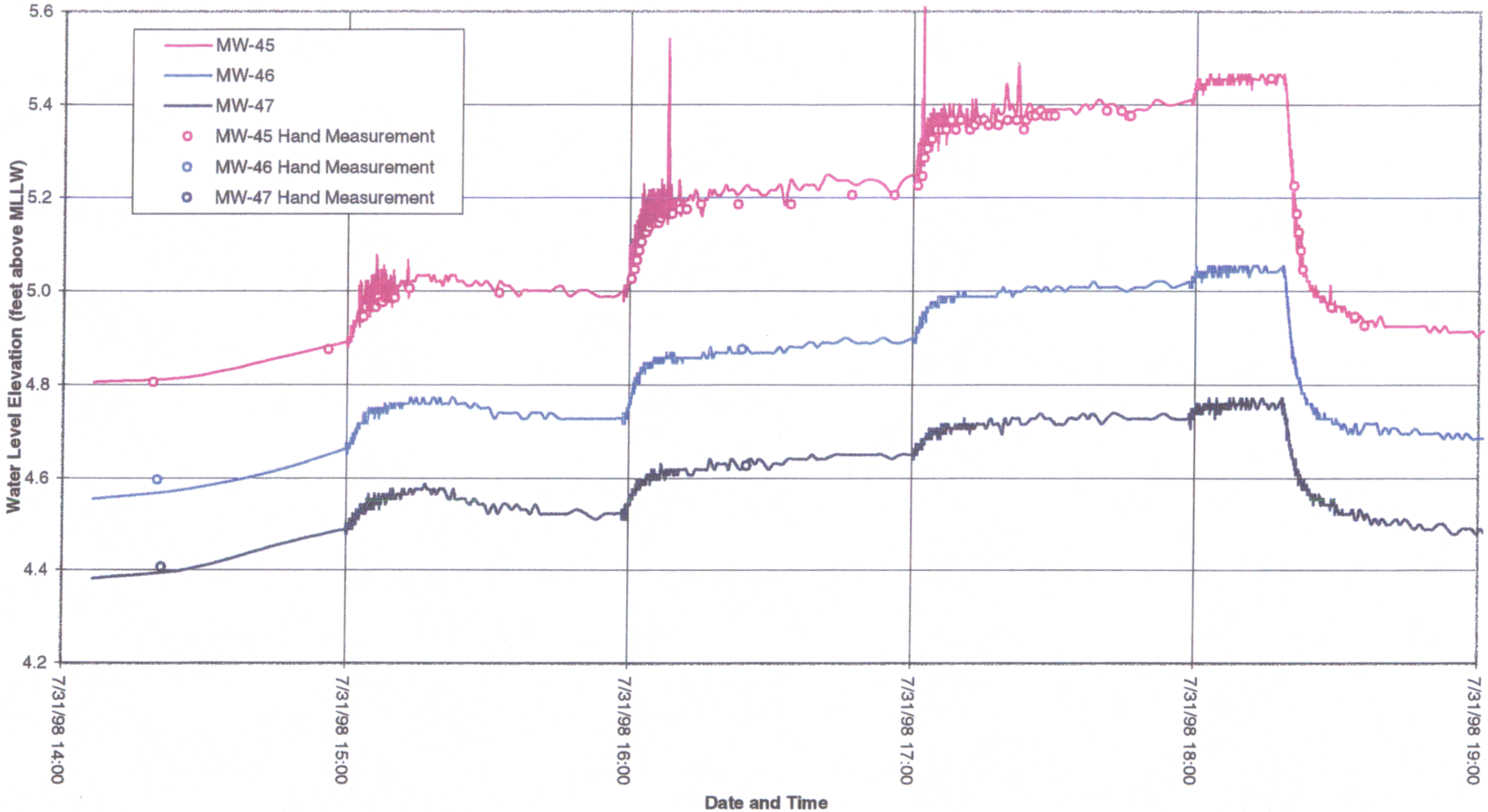
HYDROGRAPHS
INJECTION TEST
UPPER SCREEN INTERVAL



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE E1
INJECTION TEST- UPPER SCREEN INTERVAL
PUMPING WELL
JULY 31, 1998

Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE E2
INJECTION TEST - UPPER SCREEN INTERVAL
MONITORING WELLS MW-45, MW-46, AND MW-47
JULY 31, 1998

Tetra Tech EM Inc.

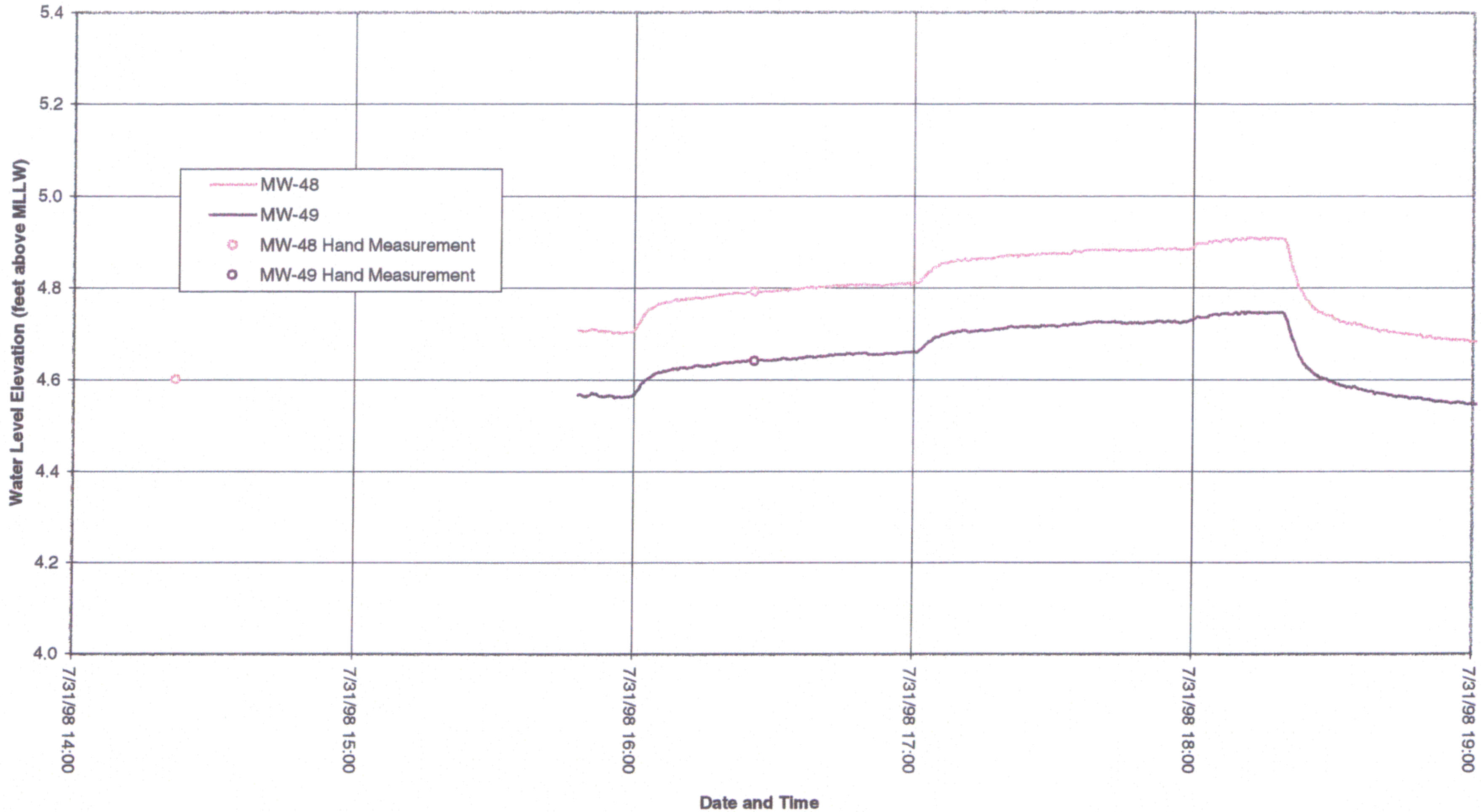


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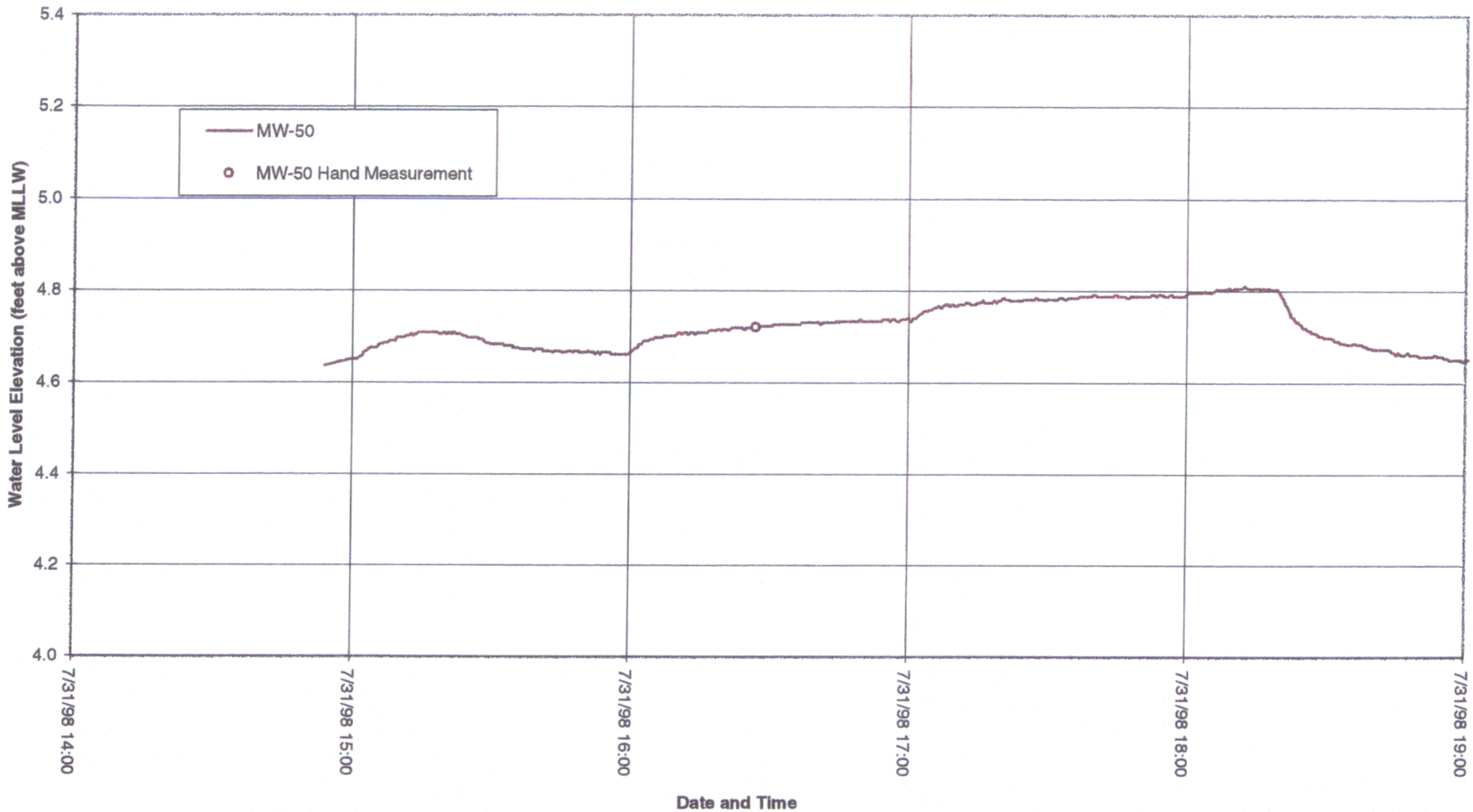
FIGURE E3
INJECTION TEST - UPPER SCREEN INTERVAL
MONITORING WELLS MW-48 AND MW-49
JULY 31, 1998

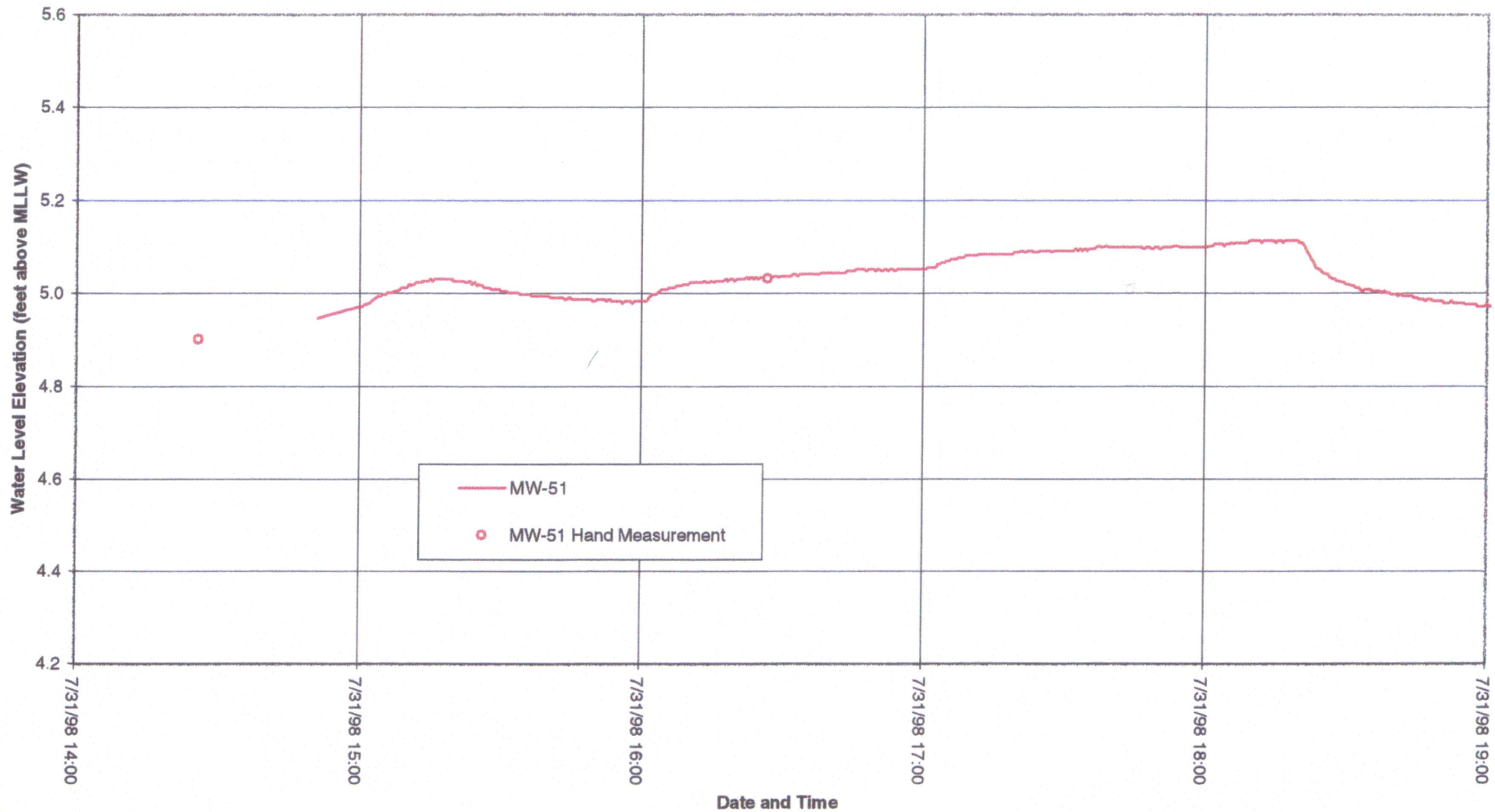
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE E4
INJECTION TEST - UPPER SCREEN INTERVAL
MONITORING WELL MW-50
JULY 31, 1998

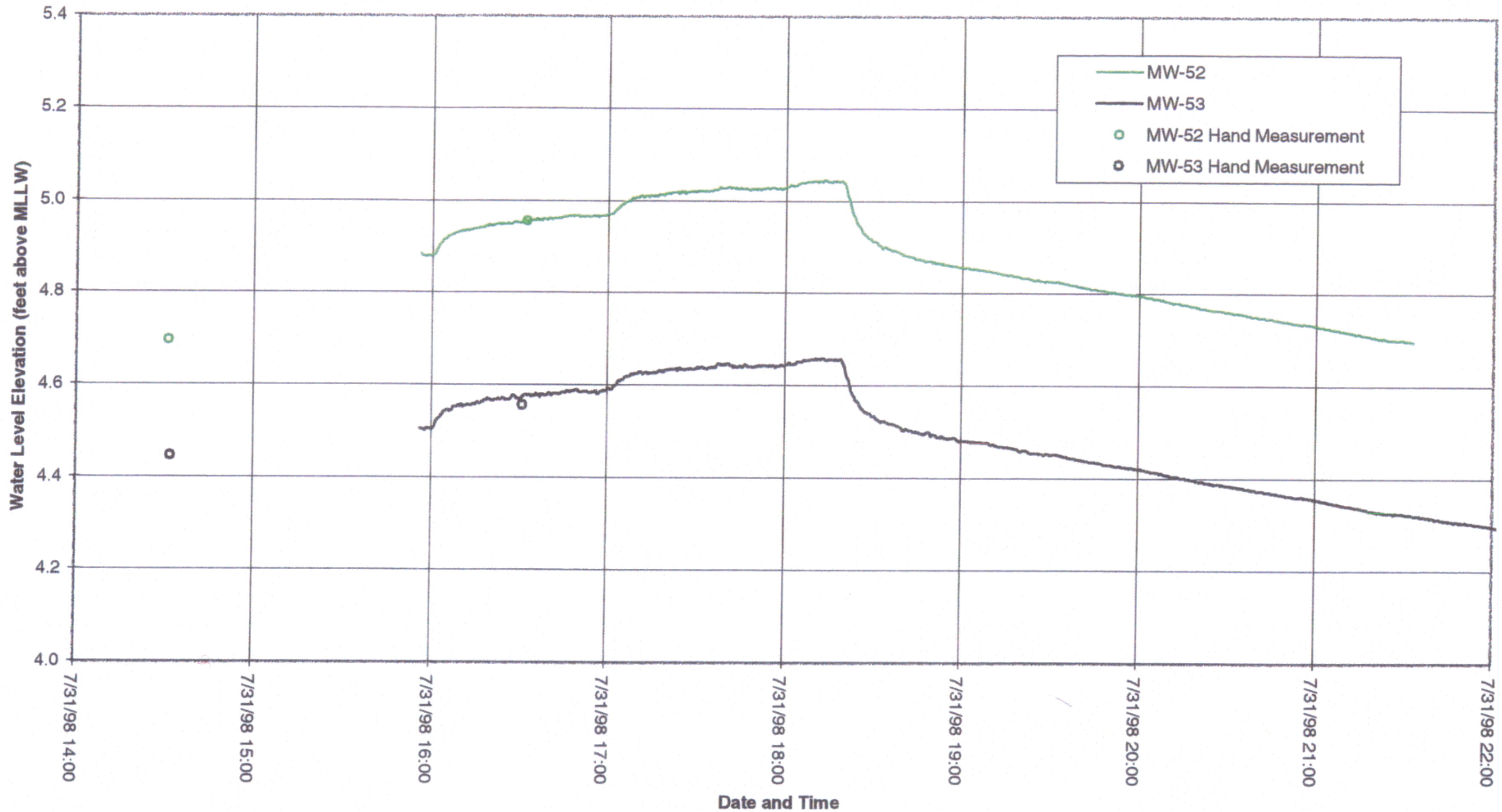
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE E5
INJECTION TEST - UPPER SCREEN INTERVAL
MONITORING WELL MW-51
JULY 31, 1998

Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE E6
INJECTION TEST - UPPER SCREEN INTERVAL
MONITORING WELLS MW-52 AND MW-53
JULY 31, 1998

Tetra Tech EM Inc.

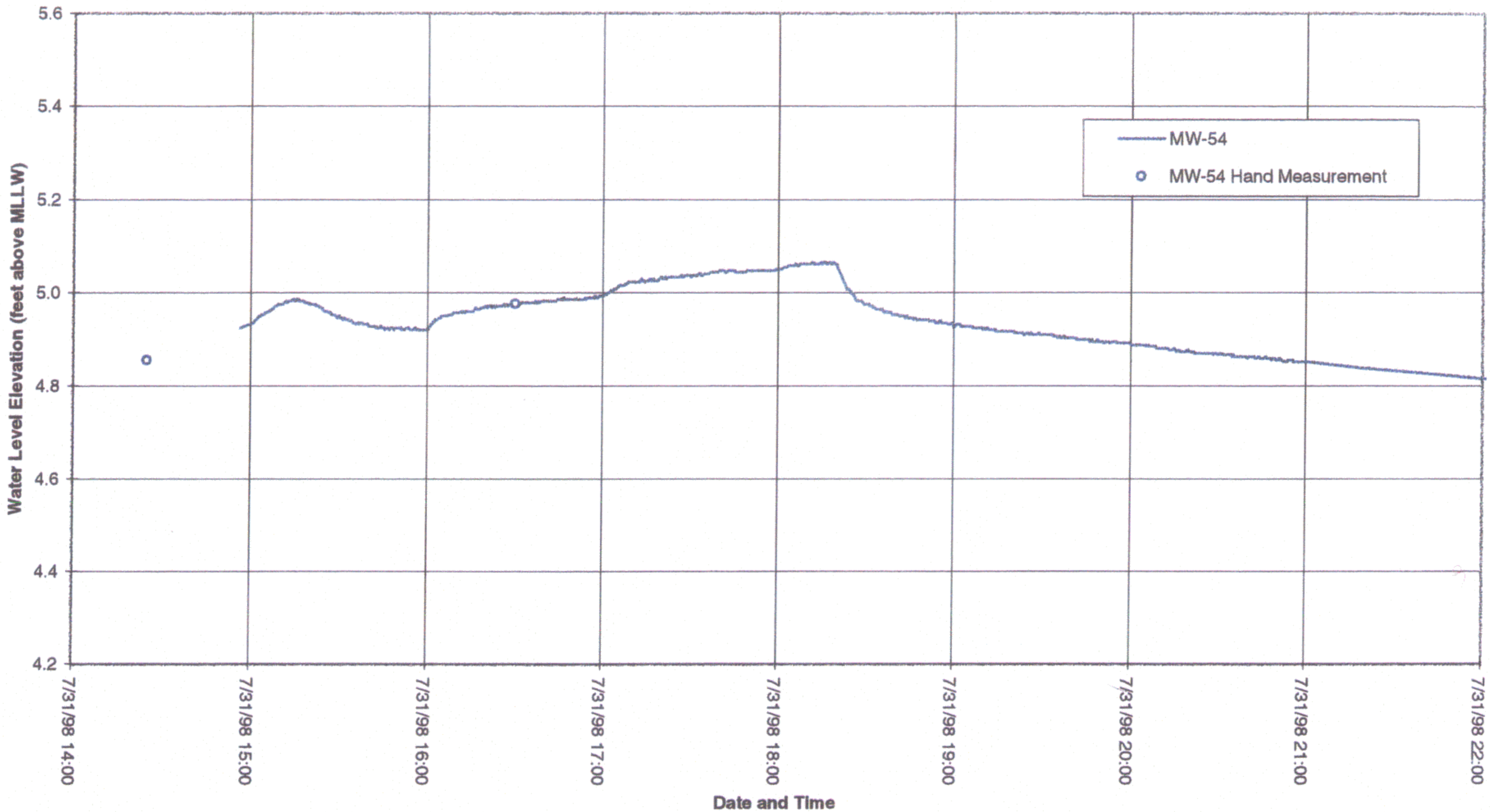


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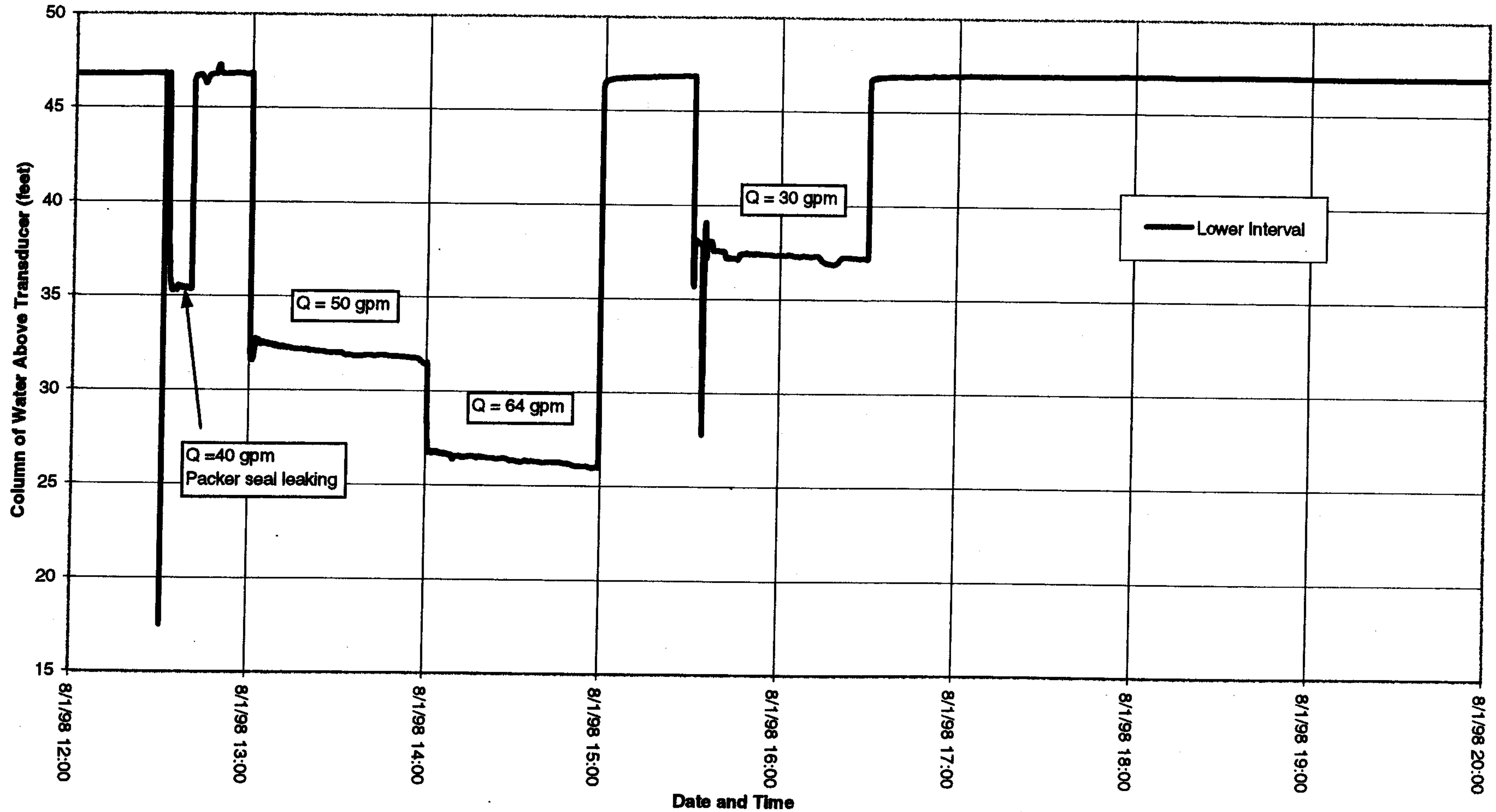
FIGURE E7
INJECTION TEST - UPPER SCREEN INTERVAL
MONITORING WELL MW-54
JULY 31, 1998

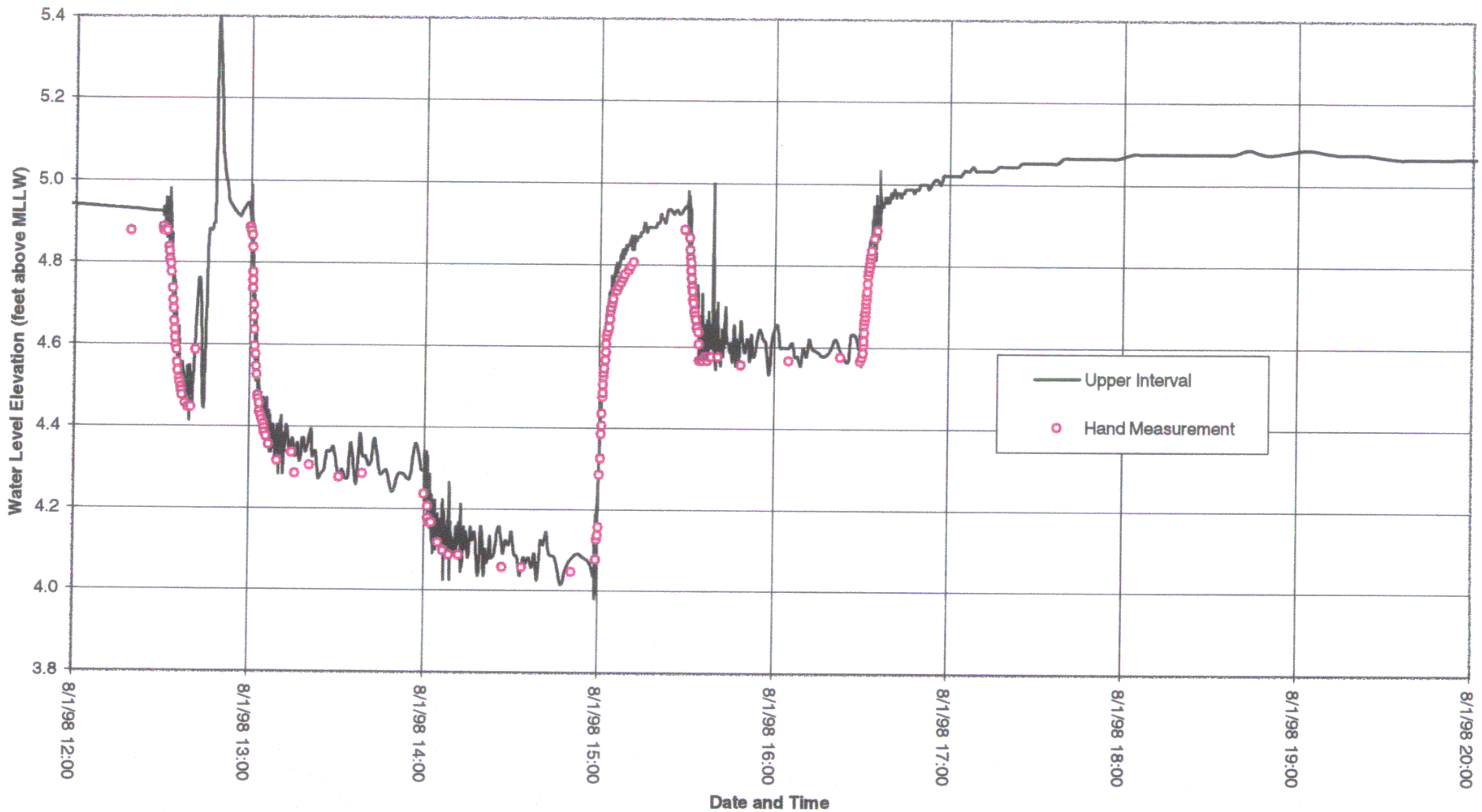
Tetra Tech EM Inc.

APPENDIX F

HYDROGRAPHS
STEP DRAWDOWN TEST
LOWER SCREEN INTERVAL



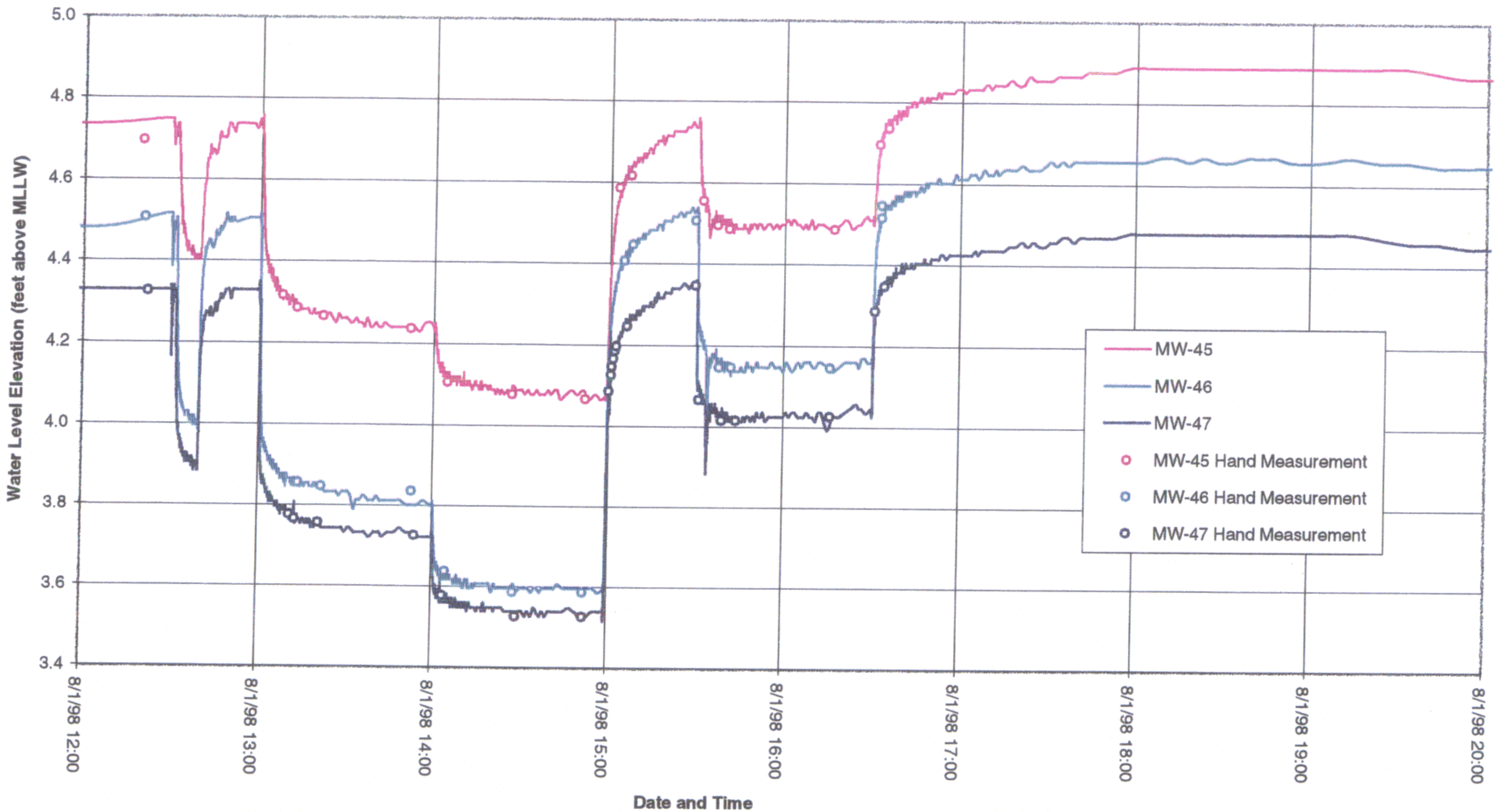
NAS NORTH ISLAND SITE 9 NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
FIGURE F1 **STEP DRAWDOWN TEST - LOWER SCREEN INTERVAL** **PUMPING WELL** **AUGUST 1, 1998**
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE F2
STEP DRAWDOWN TEST - LOWER SCREEN INTERVAL
UPPER SCREEN INTERVAL WATER LEVELS
AUGUST 1, 1998

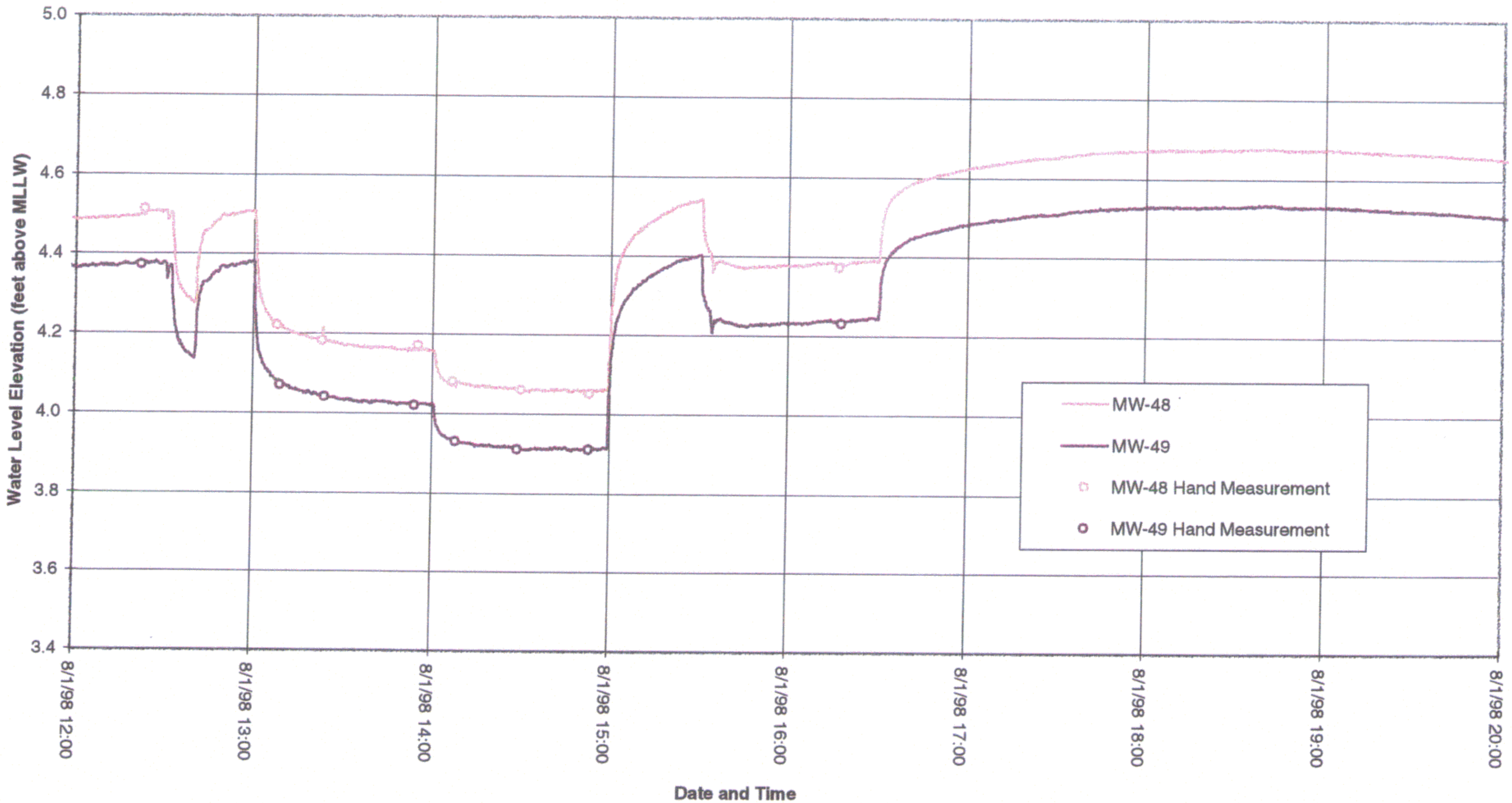
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE F3
STEP DRAWDOWN TEST - LOWER SCREEN INTERVAL
MONITORING WELLS MW-45, MW-46, AND MW-47
AUGUST 1, 1998

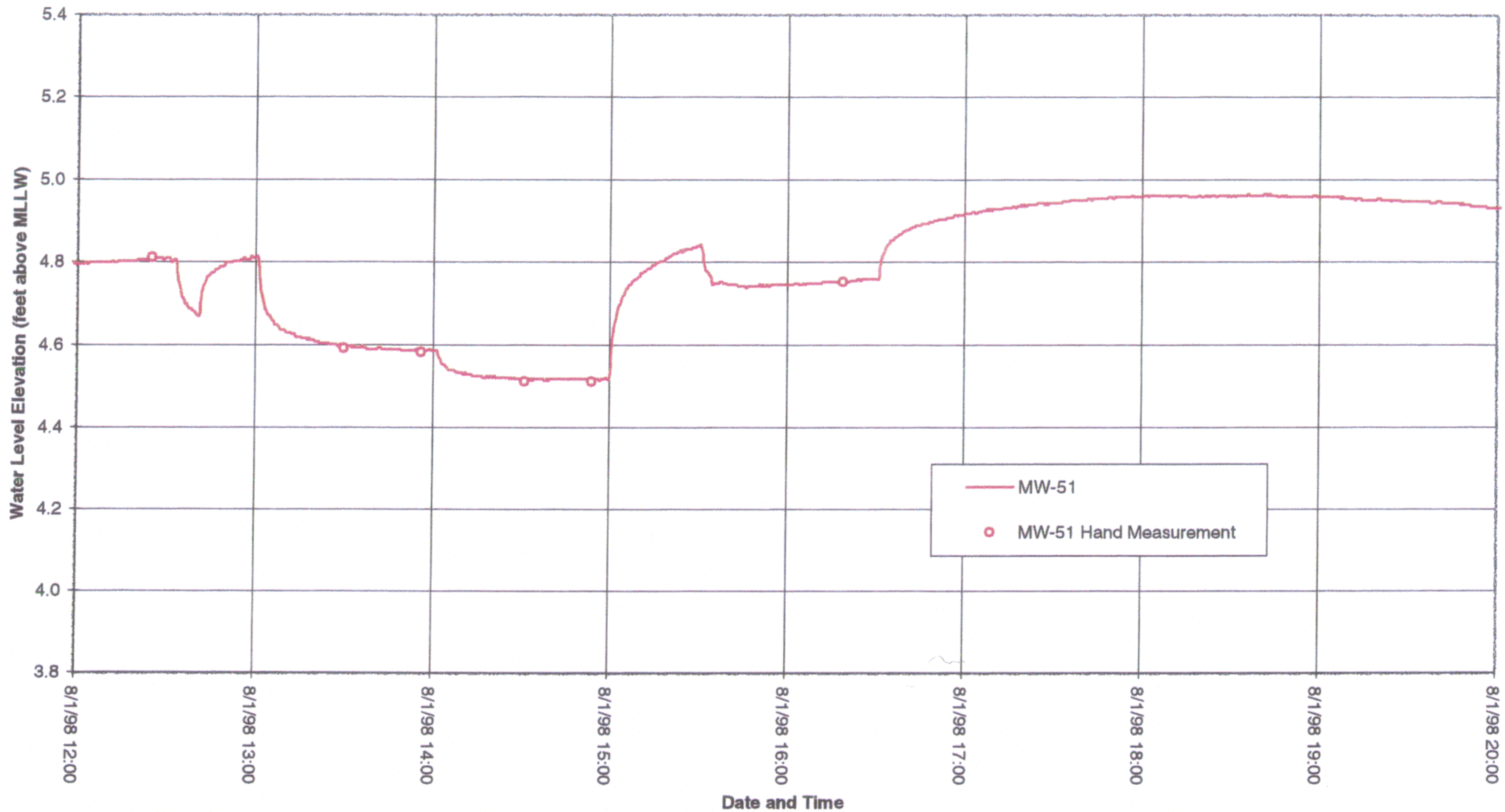
Tetra Tech EM Inc.



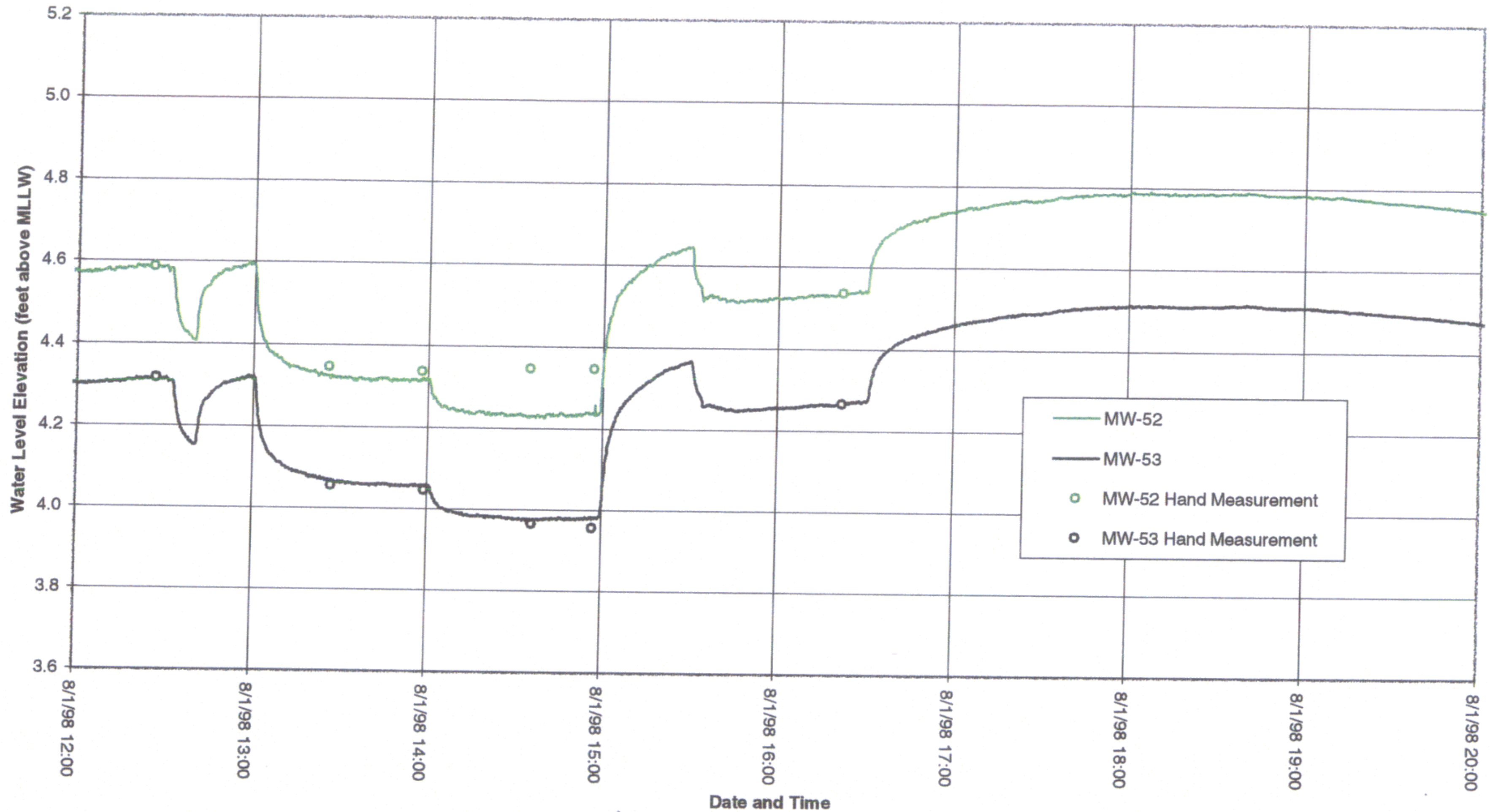
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE F4
STEP DRAWDOWN TEST - LOWER SCREEN INTERVAL
MONITORING WELLS MW-48 AND MW-49
AUGUST 1, 1998

Tetra Tech EM Inc.



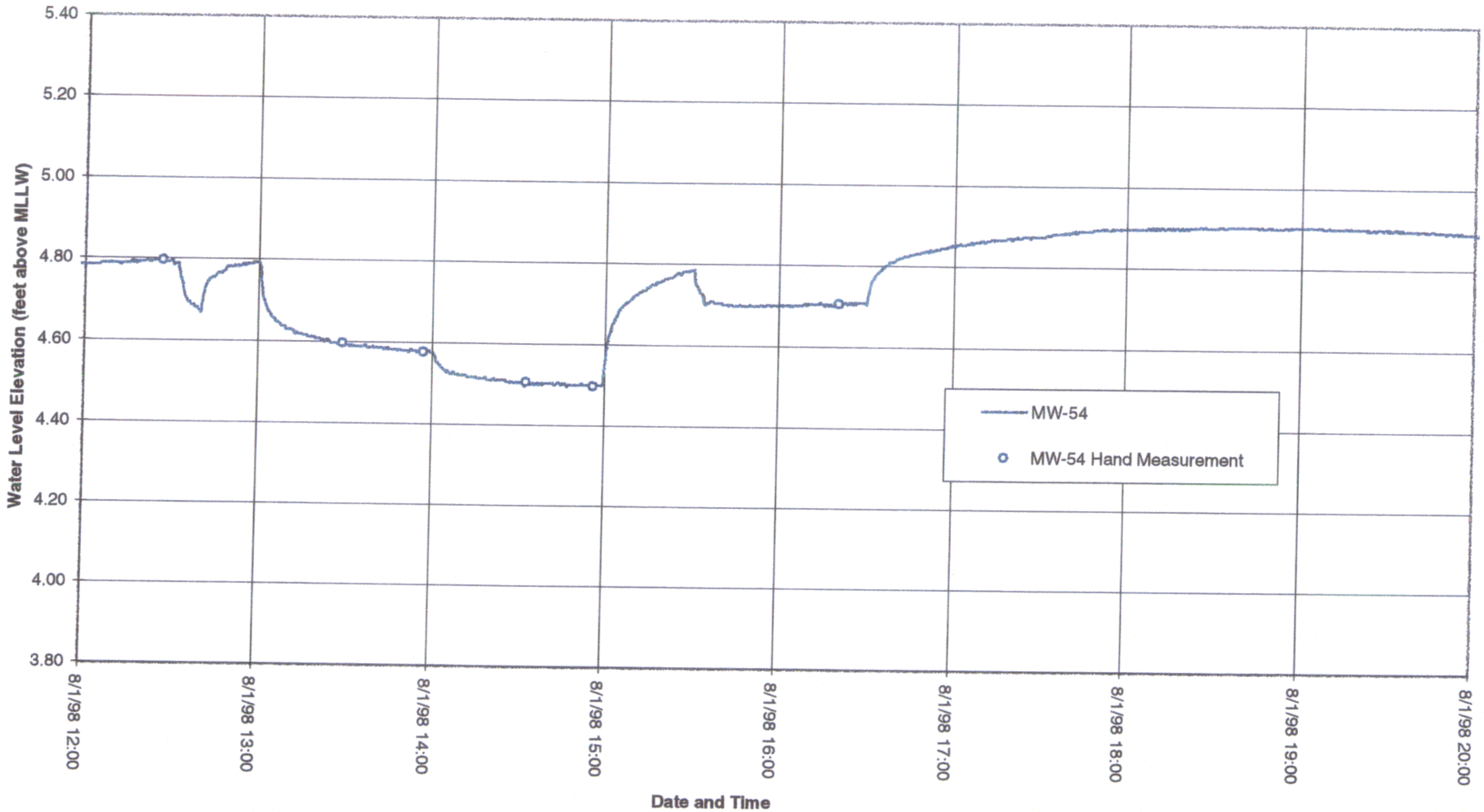
NAS NORTH ISLAND SITE 9 NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
FIGURE F5 **STEP DRAWDOWN TEST - LOWER SCREEN INTERVAL** **MONITORING MW51** **AUGUST 1, 1998**
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE F6
STEP DRAWDOWN TEST - LOWER SCREEN INTERVAL
MONITORING WELLS MW-52 AND MW-53
AUGUST 1, 1998

Tetra Tech EM Inc.



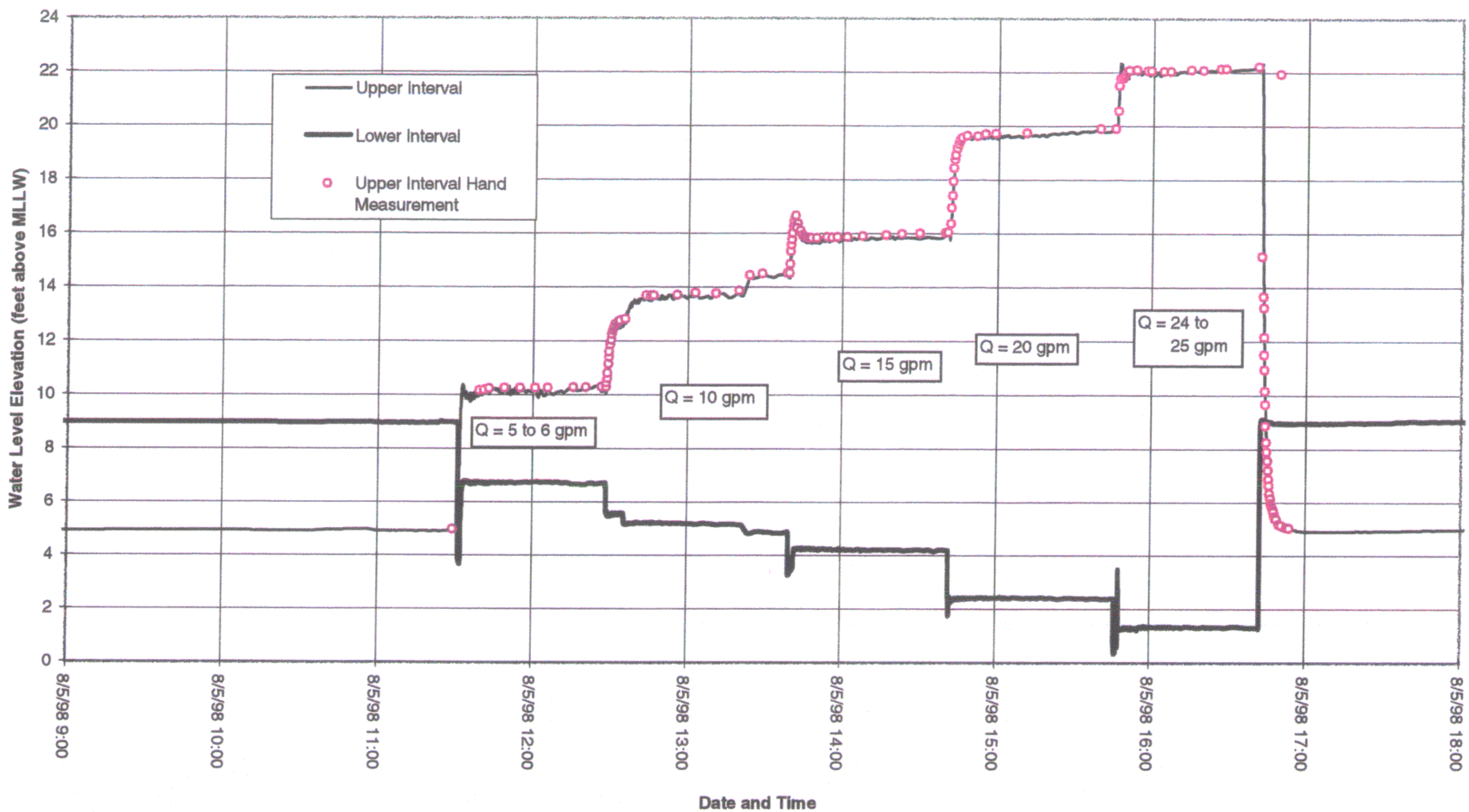
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE F7
STEPDRAWDOWN TEST - LOWER SCREEN INTERVAL
MONITORING WELL MW-54
AUGUST 1, 1998

Tetra Tech EM Inc.

APPENDIX G

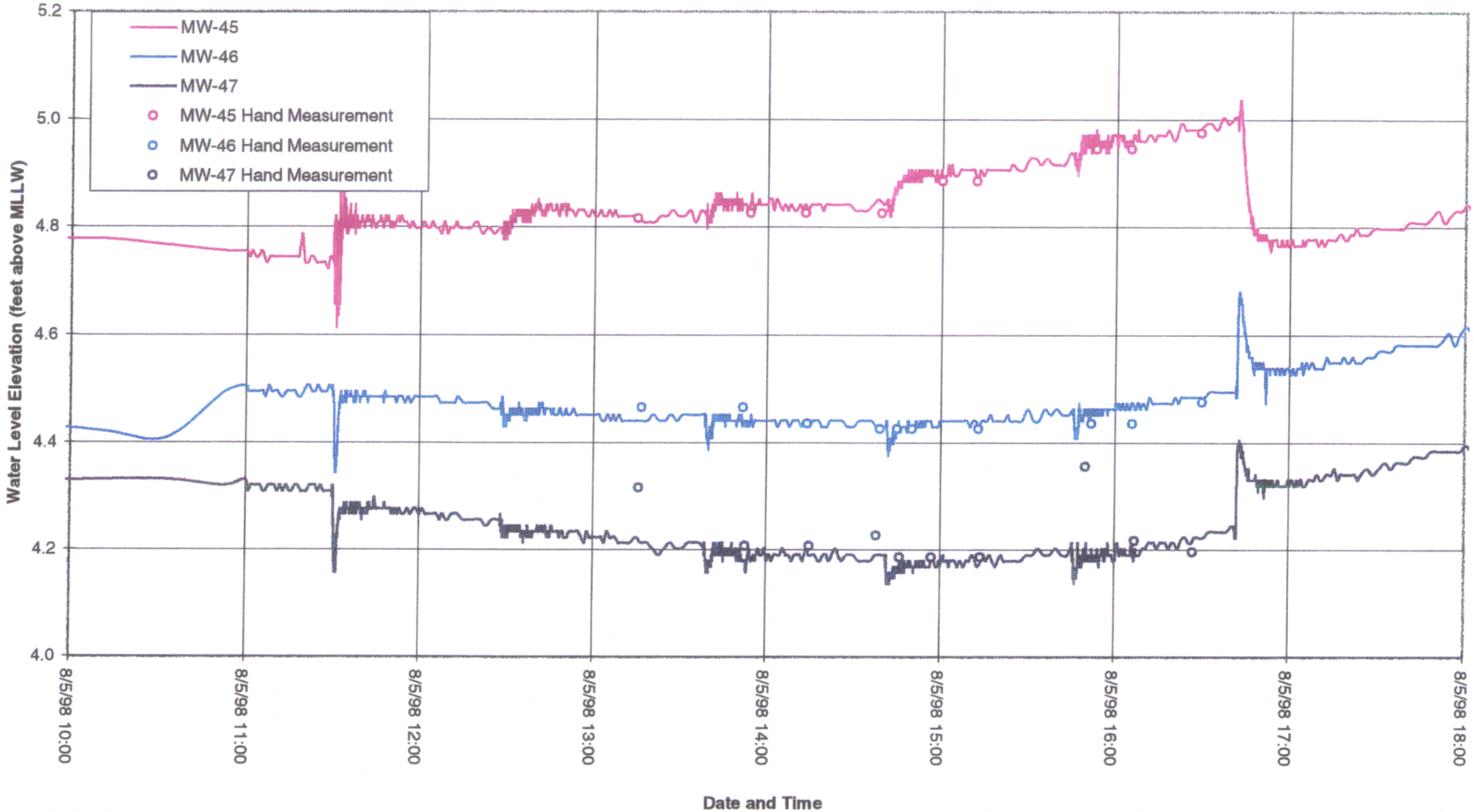
GRAPHS
DIPOLE TEST



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE G1
DIPOLE TEST
NoVOCs™ WELL PUMPING AND INJECTION
AUGUST 5, 1998

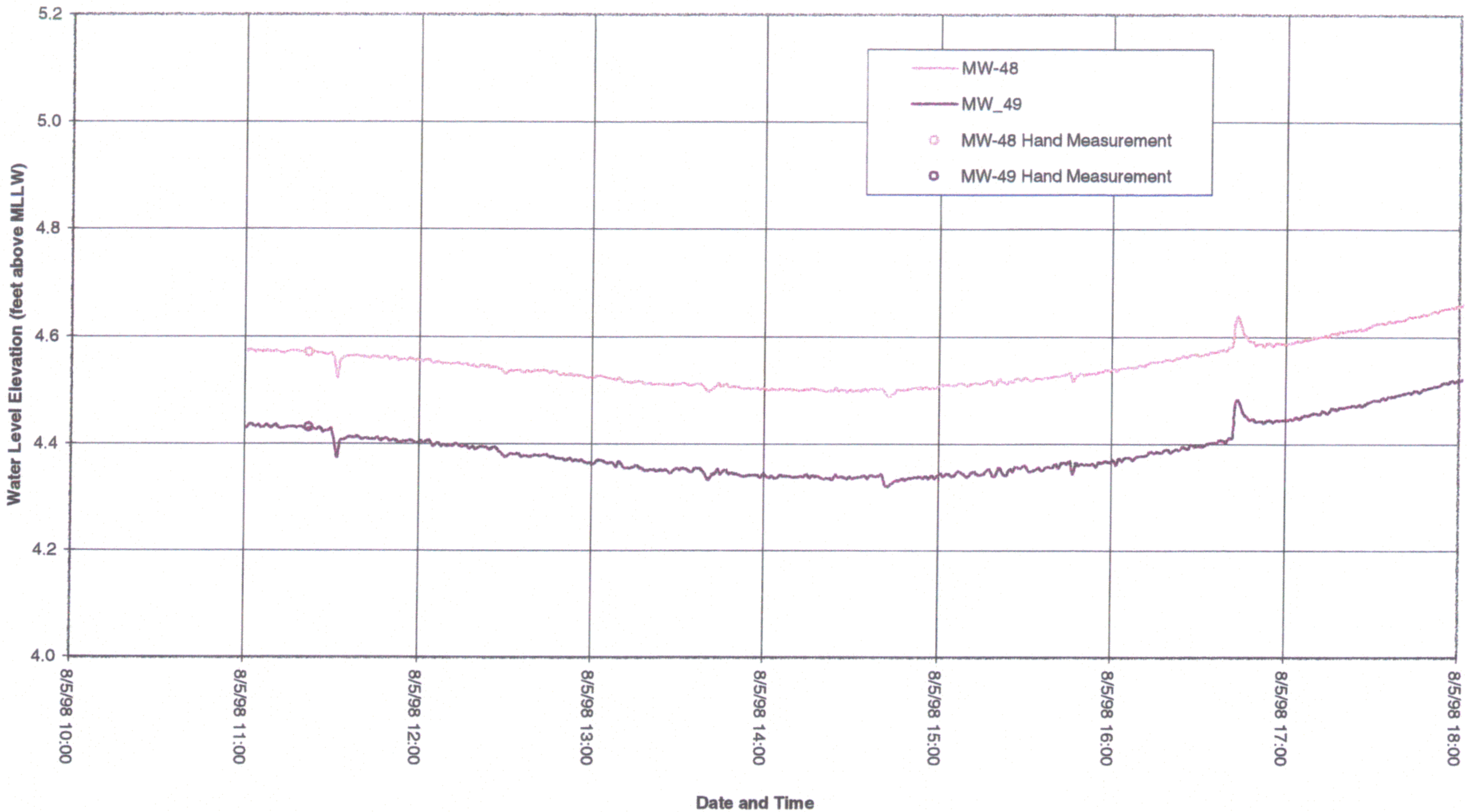
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE G2
DIPOLE TEST
MONITORING WELLS MW-45, MW-46, MW-47
AUGUST 5, 1998

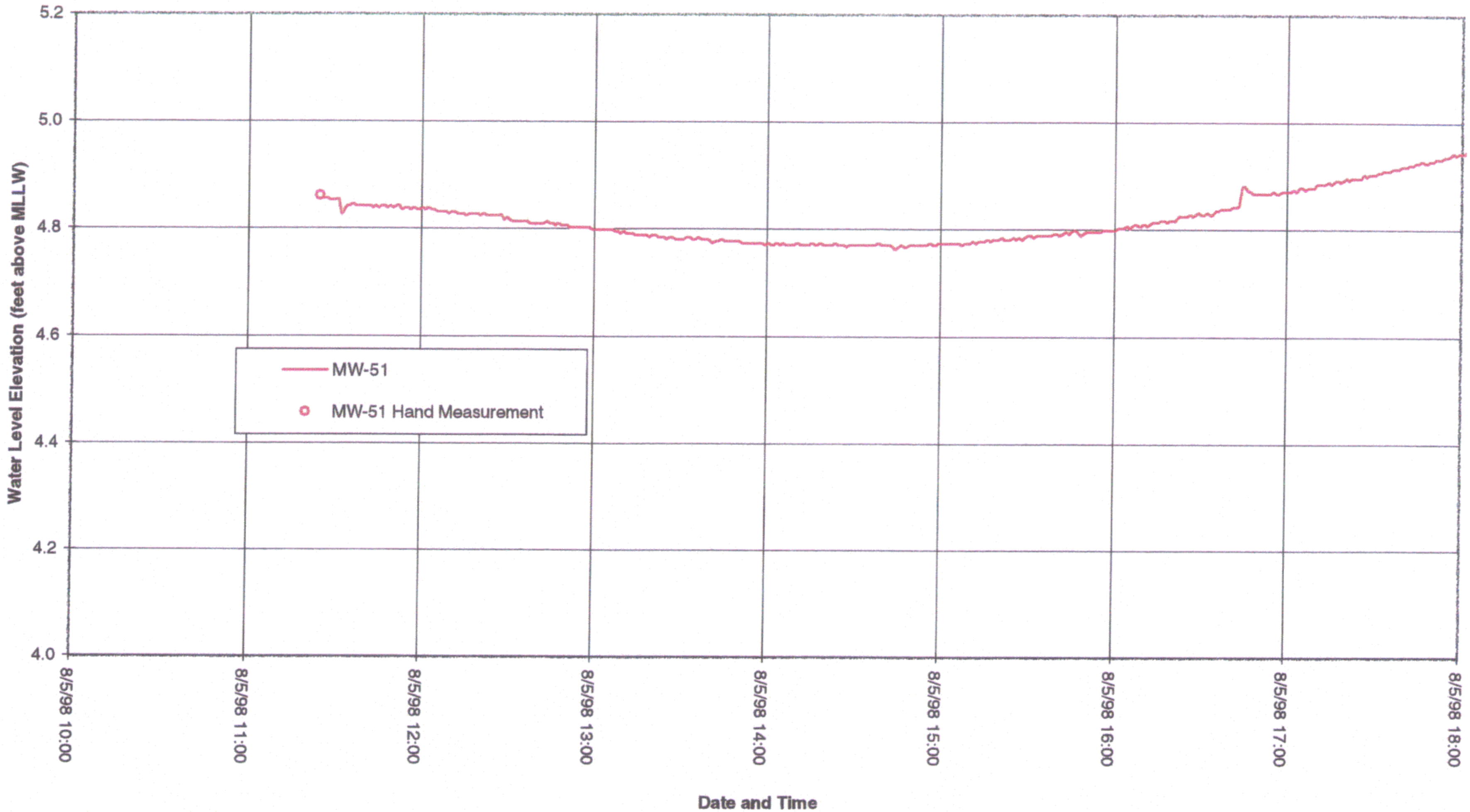
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE G3
DIPOLE TEST
MONITORING WELLS MW-48 AND MW-49
AUGUST 5, 1998

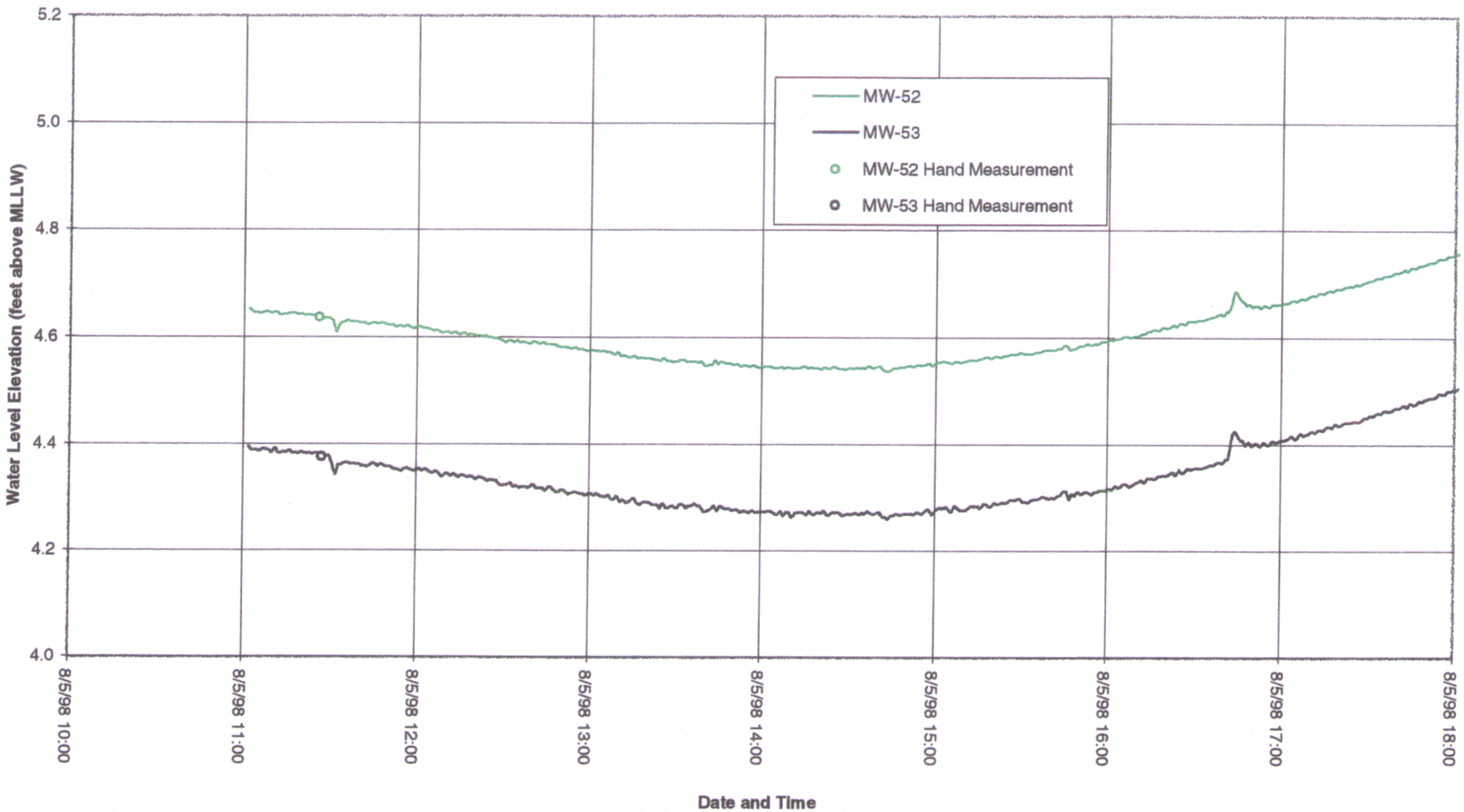
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE G4
DIPOLE TEST
MONITORING WELL MW-51
AUGUST 5, 1998

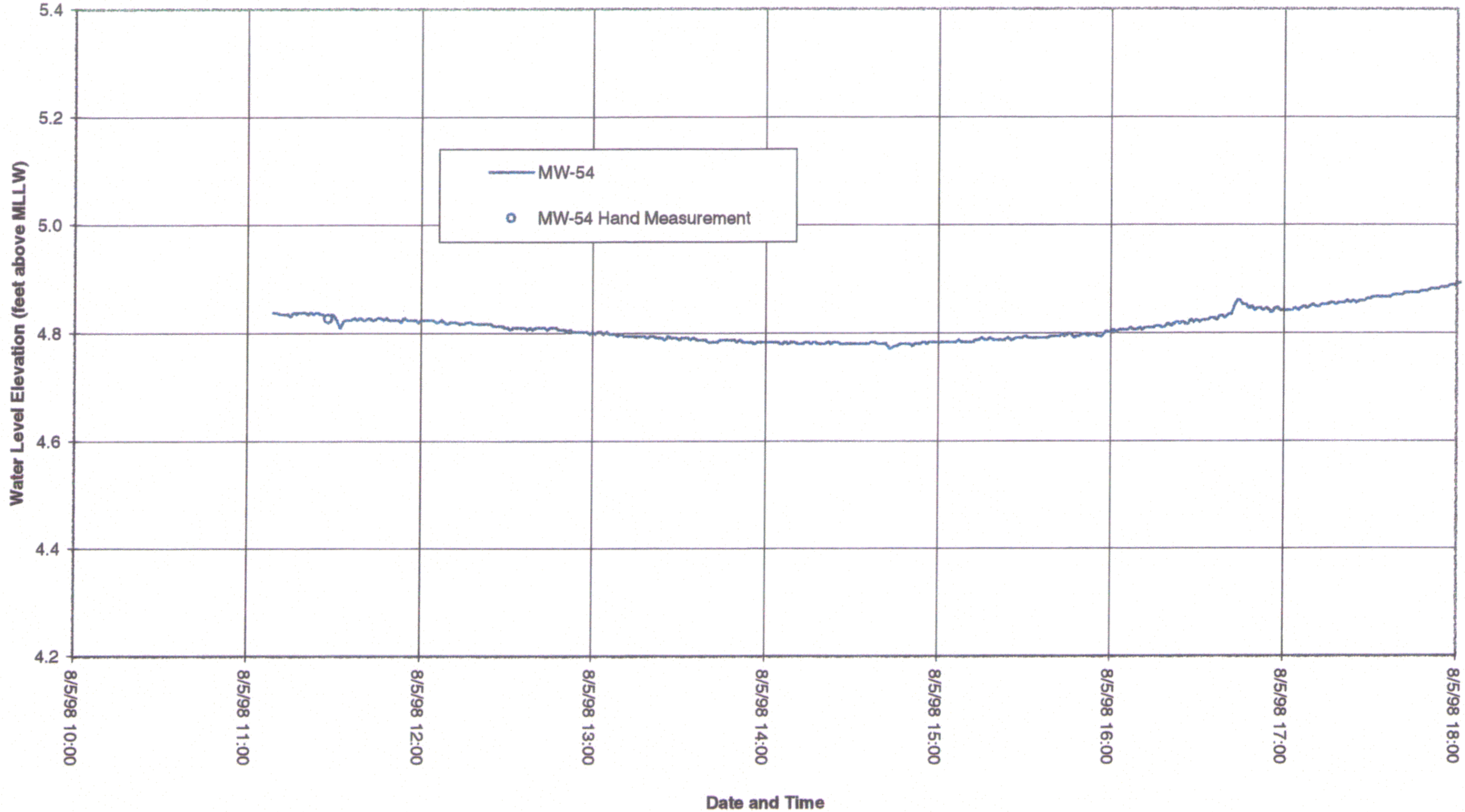
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE G5
DIPOLE TEST
MONITORING WELLS MW-52 AND MW-53
AUGUST 5, 1998

Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

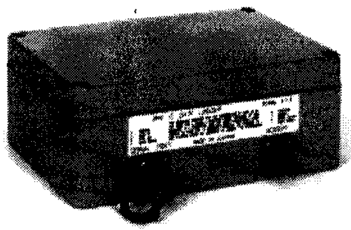
FIGURE G6
DIPOLE TEST
MONITORING WELL MW-54
AUGUST 5, 1998

Tetra Tech EM Inc.

APPENDIX H

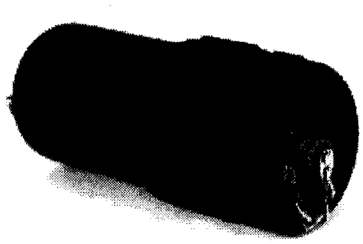
DATA LOGGER AND
PRESSURE TRANSDUCER SPECIFICATIONS

AQUISTAR® DL-SERIES DATA COLLECTION SYSTEMS



AquiStar® DL-1 System

Designed for single-channel measurements, INW's AquiStar® DL-1 data logger may be used for monitoring 4 - 20 mA sensors. Housed in a sturdy cast aluminum enclosure, it can store up to 8000 data points (24K) before downloading. A pre-installed operating program and quick connects, which complete the sensor/computer connection, make for simple installation and easy operation. The AquiStar® DL-1 also features low-power sleep modes and rechargeable batteries.



AquiStar® DL-1A System

INW's AquiStar® DL-1A data logger easily fits 4" wells and is ideal for pump/slug tests. A pre-installed operating program and quick connects, which complete the sensor/computer connection, make for simple installation and easy operation. The AquiStar® DL-1A also features low-power sleep modes and rechargeable batteries.

FEATURES

- Quick connects for easy input/output hook-up
- Pre-installed application program for trouble-free operation
- Rechargeable power supply with lithium battery back-up
- 4 - 20 mA input
- 0.1% accuracy/.025% resolution
- Easy-access PC interface
- Linear or variable rate acquisition

AquiStar® DL-4A & 8A Systems

The AquiStar® DL-4A and the DL-8A feature four or eight analog channels and three digital channels with an external power supply input connection. Housed in a weather-resistant case, each can store up to 64K of data before downloading to a PC via a RS232 serial interface. The DL-4A/8A comes equipped with a pre-installed operating program, quick connects, low-power sleep modes and rechargeable batteries.

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AQUISTAR®
DATA COLLECTION SYSTEMS

DESCRIPTION

INW's AquiStar® DL-series data loggers are an excellent option for projects that do not require sophisticated programming or communication options. Powered by internal, rechargeable batteries, the DL-series loggers are capable of monitoring water levels during pump and slug tests, and can be programmed for linear or variable rate logging with models that accommodate up to eight pressure transmitters; all operate with a minimal, PC compatible laptop. Single channel units are available in two packaging options: rugged box or 4" tube.

OPERATION

INW offers a variety of data acquisition systems to meet different site needs. Permanently-installed custom systems often require custom programming; for short-term projects, a simplified operating system may be more important than system flexibility. INW sales engineers can help choose the system that best meets your project needs.

AquiStar® DL-series data loggers are ideal for portable or permanent field data logging applications. Depending on the project, a variety of water quality sensors may be attached to a unit's input. The sensors are then configured by user-friendly PC commands to collect up to three months of data without need for service (if using the data logger's internal power supply).

Each data logger may be easily programmed to collect data in engineering units of choice as well as on a fixed or logarithmic timing sequence. Transferring data from the logger normally occurs with a portable PC where data can then be processed via the database or spreadsheet of choice.

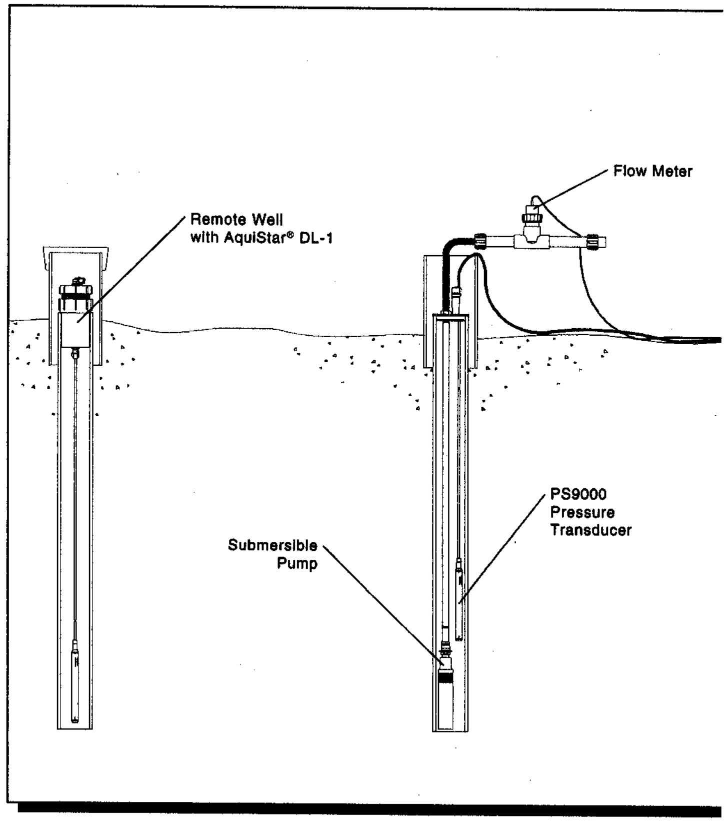
The DL-series loggers are designed to be weather-resistant and easily accommodate sensors, computer interface, output and external power hookup. Standard operating programs come pre-installed, making set-up and operation trouble-free.

OPERATION Continued

Once the unit is configured with the appropriate sensors and instructed to collect data from a portable or desktop PC, the software will direct the unit until the next service.

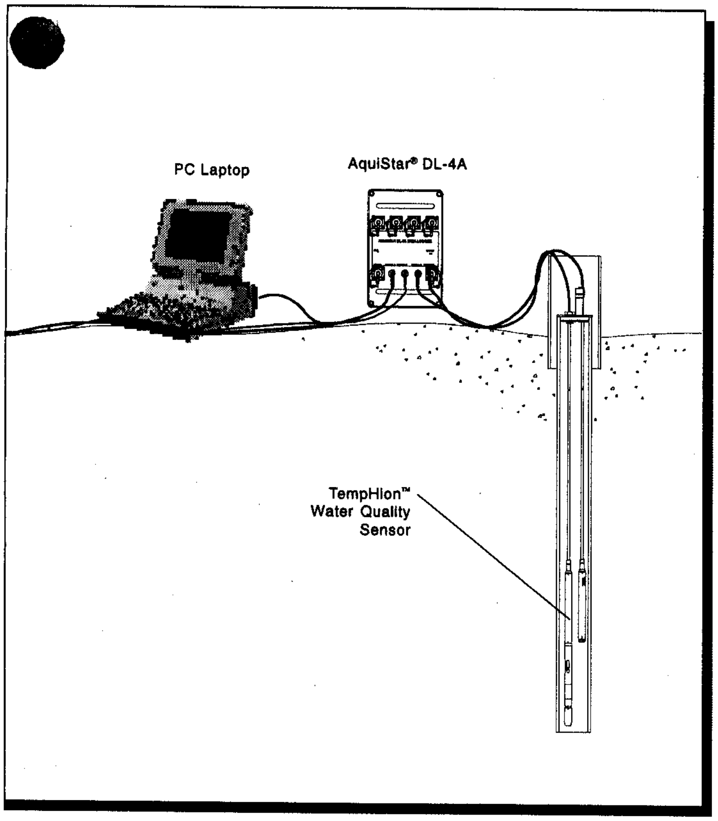
SOFTWARE

Each DL unit comes equipped with Terra 3 software. Pre-installed in the portable PC, it provides communications and data processing features such as data translation to popular graphing and spreadsheet software. Also pre-installed in the DL-series loggers are user-friendly applications programs for easy sensor measurement and logging.



TYPICAL APPLICATIONS

- Stormwater discharge monitoring
- Pump and slug tests
- Water quality monitoring
- Irrigation control
- Marine and estuary studies
- Tank monitoring
- Flow monitoring
- Tidal influence studies
- Tracer tests
- Salt water intrusion monitoring
- Stream stage



SPECIFICATIONS

AquiStar® DL-1

Channels	1 analog
Sensor excitation	5 - 18 Volts DC
Signal conditioning	0 - 20 mA
Resolution	0.025%
Accuracy	0.1%
I/O	RS232
Housing material	Aluminum
Power requirements	6 Volt DC
Operating temperature	-25°C to +50°C
Memory	24K

AquiStar® DL-1A

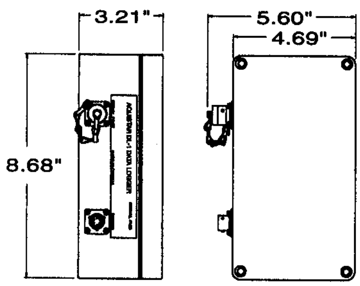
Channels	1 analog
Sensor excitation	5 - 18 Volts DC
Signal conditioning	0 - 20 mA
Resolution	0.025%
Accuracy	0.1%
I/O	RS232
Housing material	ABS
Power requirements	6 Volt DC
Operating temperature	-25°C to +50°C
Memory	24K

AquiStar® DL-4 & DL-8A

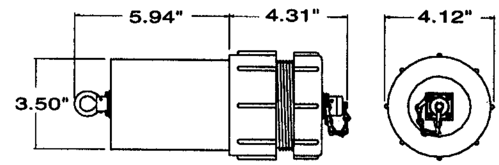
Channels	4 or 8 analog and 3 digital
Sensor excitation	5 - 10.5 Volts DC
Signal conditioning	0 - 20 mA
Resolution	0.025%
Accuracy	0.1%
Housing material	Aluminum
Analog sensor connector	6 pin Mil-Spec
Digital sensor connector	BNC
Power requirement	12 Volt DC
Operating temperature	-25°C to +50°C
Memory	64K (expandable)

1-800-776-9355

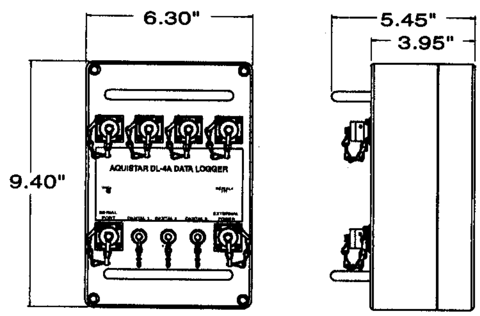
AQUISTAR®
DATA COLLECTION SYSTEMS
DIMENSIONS



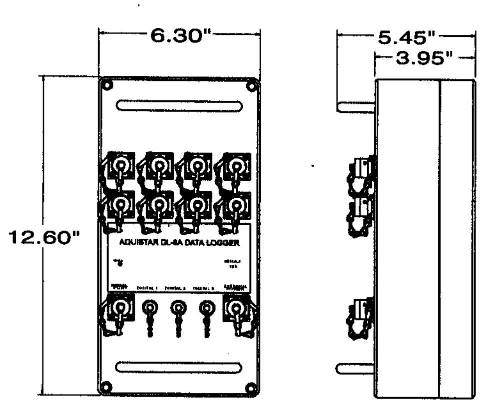
DL-1 (Box)



DL-1A (Tube)



DL-4A



DL-8A

HOW TO ORDER

- Choose the appropriate data logger.
- Order one accessory kit per operator. (Contact INW for a full list of accessories)
- Order additional sensors and cable as needed.

6D100	DL-1 Single Channel AquiStar® Data Logger
6D200	DL-1A Single Channel AquiStar® Data Logger
6D400	DL-4A Four Channel AquiStar® Data Logger
6D800	DL-8A Eight Channel AquiStar® Data Logger
6D020	DL-1 to DL-1A AquiStar® Accessory Kit
6D025	DL-4A to DL-8A AquiStar® Accessory Kit
6D050	DL-Series AquiStar® Spare Battery
6D045	(6V) DL-Series AquiStar® Battery Charger
3A010	DL-Series AquiStar® External Power Cable
6D035	AquiStar® DL-Series Serial Cable
6D040	Nine-to-DB25 AquiStar® Serial Cable Adapter
6D075	Spare AquiStar® DL-1A Manual
6D085	Spare AquiStar® DL-4A to DL-16A Manual
6D030	DL-Series Terrasys 3.0 Software Package

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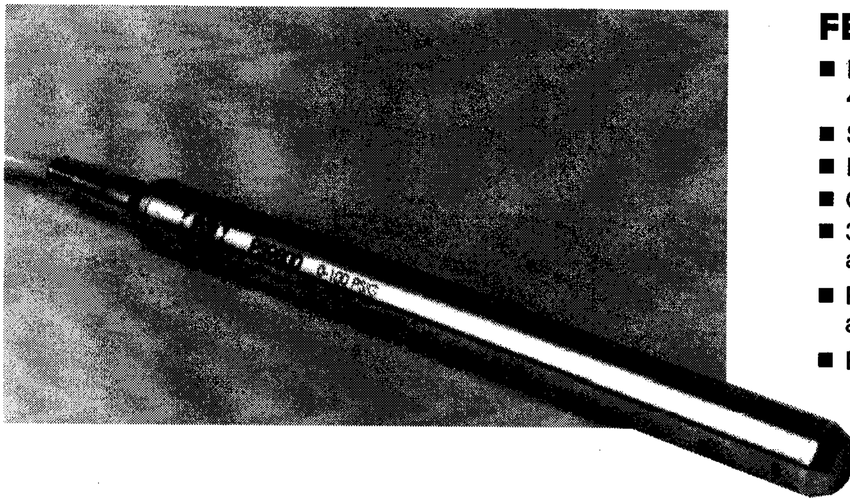
Sales and Service Locations
14902 NE 31st Circle, Redmond • Washington 98052 USA
(425) 885-3729 • (425) 867-0404 FAX • info@inwusa.com
4620 Northgate Boulevard, Suite 170 • Sacramento, California 95834
(916) 922-2900 • (916) 648-7766 FAX • inwsw@inwusa.com

17423 Village Green Drive • Houston, TX 77040
(713) 983-7623 • (713) 983-7629 FAX • inwtx@inwusa.com

1-800-776-9355
http://www.inwusa.com

PS9800 SUBMERSIBLE PRESSURE/TEMP. TRANSMITTER



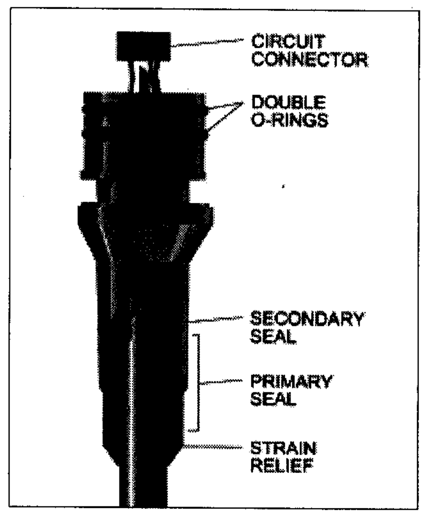
FEATURES

- Industry standard, two-wire, 4-20mA configuration
- Small diameter
- Improved noise immunity
- Optional temperature channel
- 316 stainless steel, Viton® and Teflon® construction
- Polyethylene, polyurethane and FEP Teflon® cable options
- Enhanced transient protection

DESCRIPTION

INW's patented PS9800 submersible pressure transmitter represents the latest in state-of-the-art level measurement technology. Building on years of successful experience, this industry standard two-wire, 4-20 mA device offers improved noise immunity, thermal performance and transient protection. In addition to reverse polarity protection, under-current and over-current limitation is featured on both transmitter channels. An optional 4-20 mA temperature measurement is available as a second channel within the device.

The updated cable harness design reduces the probability of leakage and protects the cable jacket from damage by providing double-sealing; 316 stainless steel, Viton® and Teflon® construction increases corrosion resistance. The transmitter's end cone is interchangeable with a 1/4" NPT inlet which allows for increased application use, easy hookup and field calibration. The modular-designed PS9800 may be easily factory serviced and repaired.



PS9800 cable harness design showing double seal and strain relief.

OPERATION

The PS9800 pressure transmitter is powered by a datalogger or control system. The internal electronic circuit controls the amount of current flowing through the loop based on the signal from the internal pressure sensor. An above-surface probe will draw 4 mA and once submerged, the current flow increases linearly with pressure (or depth). At full-scale pressure (depth), the transmitter will draw 20 mA. A data acquisition/or control system then measures this current and computes the pressure or level.

APPLICATIONS

Due to its rugged construction and proven reliability, the PS9800 is used successfully to monitor groundwater, well, tank and tidal levels, as well as for pump testing and flow monitoring.

INW

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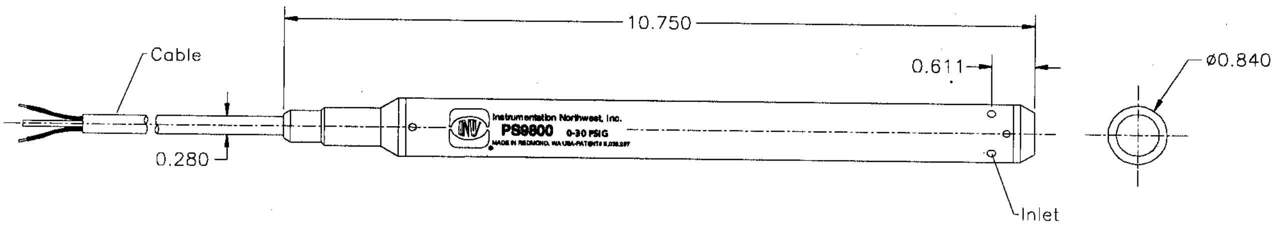
PS9800 SUBMERSIBLE PRESSURE/TEMP. TRANSMITTER

DIMENSIONS AND SPECIFICATIONS



HOW TO ORDER

- Choose the transmitter with the required pressure range.
- Determine cable type and specify length.
- Contact INW for a full list of accessories.

3C251	5 PSIG	**3C256**	50 PSIA
3C252	15 PSIG	**3C257**	100 PSIG
3C253	30 PSIG	**3C258**	100 PSIA
3C254	30 PSIA	**3C275**	300 PSIG
3C255	50 PSIG		

6E540	Vented PU INW Label	**6E542**	Vented HDPE
6E543	Vented FEP INW Label		

3C280	Temperature Option	**6E400**	M6 Connector

Information in this document is subject to change without notice.

MECHANICAL

TRANSMITTER

Body Material	316 stainless steel
Wire Seal Materials	Viton® and Teflon®
Desiccant	High- and standard-capacity packs available
Terminating Connector	Available
Weight	.75 lbs.

CABLE

OD	0.28" maximum
Break Strength	138 lbs.
Maximum Length	2000 feet
Weight	4 lbs. per 100 feet

ELECTRICAL

Pressure

Static Accuracy (B.F.S.L. 25° C)*	±0.25% FSO (maximum) ±0.1% FSO (typical) *0.1% available on request.*
Thermal Error (0-50° C, reference 25° C)	±2.0% FSO (maximum) ±0.8% FSO (typical)
Maximum Zero Offset at 25° C	±0.5% FSO
Sensitivity Accuracy at 25° C	±0.25% FSO (maximum) ±0.125% FSO (typical)
Maximum Temperature Error	±2.0% FSO
Over Range Protection	2x (except 300 PSIA)

Temperature

Transmitter Voltage	9-24 VDC, 100 ms warm-up 0-50° C >> 4-20 mA
Accuracy (100 ms warm-up)	±0.75° C (maximum) ±0.3° C (typical)
Compensated Temperature Range	0 - 50° C
Operating Temperature Range	-5° C to 70° C

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14902 NE 31st Circle, Redmond • Washington 98052 USA
(425) 885-3729 • (425) 867-0404 FAX • info@inwusa.com
4620 Northgate Boulevard, Suite 170 • Sacramento, California 95834
(916) 922-2900 • (916) 648-7766 FAX • inwsw@inwusa.com

17423 Village Green Drive • Houston, TX 77040
(713) 983-7623 • (713) 983-7629 FAX • inwtx@inwusa.com

1-800-776-9355
http://www.inwusa.com